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SCIENCE PLAN for the ALASKA SAR FACILITY PROGRAM

Phase 1: Data From the First European Remote Sensing Satellite, ERS-1

by the Alaska SAR Facility Prelaunch Science Working Team

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16. Abstract

Science objectives, opportunities and requirements are discussed for the utilization of data from the Synthetic Aperture Radar (SAR) on the European First Remote Sensing Satellite, to be flown by the European Space Agency in the early 1990s. The principal applications of the imaging data are in studies of geophysical processes taking place within the direct-reception area of the Alaska SAR Facility in Fairbanks, Alaska, essentially the area within 2000 km of the receiver. The primary research that will be supported by these data include studies of the oceanography and sea ice phenomena of Alaskan and adjacent polar waters and the geology, glaciology, hydrology, and ecology of the region. These studies focus on the area within the reception mask of ASF, and numerous connections are made to global processes and thus to the observation and understanding of global change. Processes within the station reception area both affect and are affected by global phenomena, in some cases quite critically. Requirements for data processing and archiving systems, prelaunch research, and image processing for geophysical product generation are discussed.

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From the Chena Hot Springs, Alaska Meetings
July 1987 and August 1988

September 1, 1989

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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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FOREWORD

This Science Plan was assembled from contributions by the Alaska SAR Facility Prelaunch Science Working Team (PSWT) appointed by NASA; the group membership is shown below. Future publications will reflect changes to the Science Plan brought about by the augmentation of the ASF data products by reception and processing of observations from the Japanese ERS-1 and RADARSAT.

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PREFACE

During the next five years, three spacecraft will carry Synthetic Aperture Radars (SARs) in near-polar orbits. They are the First European Remote Sensing Satellite, ERS-1, flown by the European Space Agency (ESA), the First Earth Resources Satellite, J-ERS-1, to be flown by the National Space Development Agency of Japan (NASDA), and RADARSAT, to be flown by the Canada Centre for Remote Sensing (CCRS). NASA has signed Memoranda of Understanding (MOU) with ESA and NASDA to acquire data at the Alaska SAR Facility (ASF) at the University of Alaska, Fairbanks (UAF); a similar MOU is under negotiation with CCRS. SAR data derived from these missions will be processed to images, and archived for distribution to scientists involved in a broad range of investigations of the oceans, ice cover, and land. In order to provide an overview of these research applications and to provide guidance toward requesting specific data coverage from the mission agencies, NASA asked a Prelaunch Science Working Team, or PSWT, to formulate this Science Plan for the ASF during the initial period of data acquisition, called Phase I, when data will be acquired and processed from ERS-1. ERS-1 is due to be launched in late 1990 or early 1991 and to remain functional for up to three years.

The PSWT has met twice, in August 1987 and July 1988, and panels of the PSWT have met a number of times in the past two years. The purpose of these meetings was to determine the science objectives for Earth science investigations of greatest potential addressable with the ERS-1 data and to specify the program required for the full utilization of the data in these investigations. The ERS-1 data will be taken only while the spacecraft is within range of data transmission to ASF, an area of about 3000 km radius, while the follow-on satellites, J-ERS-1 and RADARSAT, will carry on-board data recorders making their data global in nature. Future science plans will address use of the follow-on data sets.

These flight systems will supply key global SAR data to Earth science investigators over the next eight years. The experience gained from the ASF science program, with that from the aircraft SAR program and the flight of Shuttle Imaging Radar, will be essential to the effective utilization of SAR data from the Earth Observing System (Eos) and to our progress in understanding the Earth system. The program that has been initiated by this Science Plan is thus a key step in our long-range plans. I take this opportunity to thank the PSWT for their careful and thoughtful work in putting together this plan.

S. G. Tilford

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ALASKA SAR FACILITY SCIENCE PLAN

EXECUTIVE SUMMARY

Information obtained by the interpretation of radar images from Synthetic Aperture Radar, or SAR, has proven to be useful to a number of scientific disciplines including oceanography, geology, ecology, hydrology and glaciology. A particularly attractive application has been in the study of polar oceanography through SAR observations of the dynamics and character of the ice cover of the polar seas. To capitalize on the research potential and ultimately on the operational capabilities suggested by existing data sets, the deployment of SAR systems on three satellites is planned for the early 1990s. These satellites are the First European Remote Sensing Satellite, ERS-1, under development by the European Space Agency, the Japanese First Earth Resources Satellite, J-ERS-1, under development by the National Space Development Agency (NASDA) of Japan, and RADARSAT, under development by the Department of Energy, Mines and Resources (EMR) of Canada. In collaboration with these satellite programs, NASA has instructed the Jet Propulsion Laboratory of the California Institute of Technology and the University of Alaska Fairbanks to design, implement and operate a ground station at Fairbanks to receive and process the SAR data from ERS-1 (in such a fashion that an upgrade to accommodate the other two satellites can be readily accomplished) and to help develop a program that utilizes the data effectively in a wide variety of scientific disciplines. The ground station is called the Alaska SAR Facility or ASF. The period of time in which only ERS-1 data are received and processed is called Phase 1. Future documents will address an extended science and applications program for the later phases of ASF when data from J-ERS-1 and RADARSAT will become available.

The ERS-1 satellite will be placed in sun-synchronous orbit inclined near 98° at an altitude of 750 km. Its SAR will operate at C-band (5.25 GHz) with an incidence angle of 23°. While J-ERS-1 and RADARSAT will carry tape recorders to obtain SAR observations from distant locations, ERS-1 can collect and transmit SAR image data only while in communication range of a ground station such as the ASF. This communication range is generally about 2000 km, and its projection on a map is called a station mask.

The ground system planned for the Alaska SAR Facility consists of three major subsystems, the Receiving Ground Station, the SAR Processor System, and the Archive and Operations System. The Receiving Ground Station performs the satellite acquisition and tracking function and the reception and demodulation of the SAR signal; the SAR Processing System processes the SAR signal into images at various resolutions as specified by the investigators; and the Archive and Operations System maintains a catalog and archive of the signal data and SAR images and performs mission and station operations planning to support ASF activities.

A Science Working Team (SWT) will be affiliated with the ASF to perform the scientific research. NASA plans to select the Science Working Team by peer-review of proposals submitted in response to a solicitation. Should funding not be available for this solicitation, NASA will modify the makeup of the Prelaunch Science Working Team (PSWT), an advisory group appointed jointly by the Land Processes and Oceanic Processes Branches of NASA Headquarters, to engage in the research program. The Alaska SAR Facility is designed to be capable of supporting a wide range of scientific investigations.

The scientific literature contains discussions of SAR data applied to a wide variety of investigations. Particularly notable are applications to the study of air-sea-ice interactions, oceanic waves, fronts and eddies, glacier and ice sheet characteristics and dynamics, structural

geology, tectonics and geomorphology, terrestrial ecology, and hydrologic processes. Within the station mask of ASF there are opportunities for all of these types of investigations. The combined data from all three satellites will present a unique first opportunity for scientists to do long-term monitoring of geophysical processes and climate-induced changes using high resolution imaging radar data. The need to monitor the changes in the key cryospheric parameters, including those describing sea ice, glaciers, snow-cover and permafrost, as a measure of climate change is crucial, since climate simulations predict climatological changes to be largest at high latitudes.

In the field of oceanography there is a wide variety of research topics relating to both ice-free and to ice-covered oceans where the availability of SAR data offers interesting research possibilities. SAR data of sea ice supplies key information on ice: it indicates ice type, the seasonal cycle of change in the ice cover, and it can be used to generate fine-scale Lagrangian ice motion maps. Detailed observations of the circulation of the ice in both the Arctic Ocean and its peripheral seas will become possible. Such studies will greatly advance the knowledge of air-sea-ice and air-sea-ice-land processes which are at present based on observations collected from widely separated buoys and drift-platforms of opportunity. It will also be possible to make preliminary estimates of the heat and mass fluxes in different parts of the Arctic seas for different seasons of the year by monitoring the formation of leads and the transfer of undeformed ice into pressure ridges. The changes observed in the surface morphology of the ice pack resulting from deformation can be used to estimate changes in regional values for air/ice/ocean momentum transfer, thereby contributing to the more effective utilization of such values in ice dynamics models. Detailed observations of ice movement and deformation will also stimulate the development of more realistic models of the rheology of sea ice as it varies with location, season, ice thickness, and ice type. At the coastlines of ice-covered seas the interactions of ice with land are important to the behavior of the ice pack itself and to processes such as erosion and sediment transport in the near-shore region. SAR is an ideal tool in studies of air-sea-ice interactions in the marginal ice zone because the cloud cover so frequently encountered in such regions does not act as an observational barrier and because the SAR data also provides indirect information on the gravity wave field both within the ice and in the open ocean beyond the ice edge. Also important are studies of the kinematic behavior of the ice pack, in particular investigations of the probability distributions that most effectively describe the widths of, and spacings between, leads. With the predicted future climate change, major changes in sea ice extent and thickness may occur, and those changes and the processes resulting from them can best be studied using SAR observations. Finally SAR data should prove to be highly useful in initializing, updating and verifying numerical models of sea ice behavior.

For the ice-free oceans an equally interesting set of problems awaits. For example, SAR data will contribute much useful information to studies of the occurrence and evolution of mesoscale circulation features in the open ocean. It will prove useful in investigations of the surface wave climatology of Alaskan waters and in studies of the occurrence and energy distribution in the internal waves that develop in the Alaskan shelf seas. It will also contribute to investigations of the finescale sea surface windfield and its associated surface fluxes, to studies of SAR-observed surface effects resulting from interactions between gravity waves and currents with bottom topography and to investigations of the effects of surfactants on air-sea interactions. Finally, as was the case for ice-covered oceans, SAR data should prove to be extremely useful in initializing, updating, and verifying ocean wave and circulation models.

Applications of SAR data to glacier studies are envisioned in three areas of scientific and practical interest: the interactions between glaciers and climate, the dynamics of glacier flow, and the engineering hazards of glaciers. Glaciers and ice sheets are themselves products of specific climate conditions, and changes in their state indicate changes in the intensity of climate processes and can be interpreted as indicators of climate change. Of particular interest is the effect on sea level of increasing glacial melt water due to climatic warming. In addition, glaciers and ice sheets also exert a significant influence on world climate. Indeed, the complex processes of glacier flow, characterized by variable boundary conditions and the presence of water in all its phases, can lead to large scale instabilities that do not depend directly on climate variables. Glacial flow is reflected in the contours and deformation patterns of the ice at the glacier's surface, and it is SAR's sensitivity to these surface patterns and their changes that provides useful information to scientists. The engineering hazards of glaciers relate to the regulation of water supplies, to the flooding resulting from outbursts of glacier-dammed lakes, to volcano-glacier interactions and to the effects of icebergs, calved from glaciers, on shipping.

Land processes studies include topics in geology, hydrology and terrestrial ecosystems. Objectives in geology that would benefit from the use of SAR data include the determination of the character and composition of the Earth and reconstruction of its changing geologic environment. A better understanding can be achieved of land-surface, coastal and continental-shelf processes in world-wide, especially arctic and subarctic, environments because the intermediate and final configurations resulting from these processes can be observed in the ASF SAR data for both Alaska and its adjacent seas. In addition, structural mapping and interpretations of tectonic history and environmental and paleoclimatic studies would be advanced. Geologic investigations that can be pursued using data from the ASF are broadly indicated here under the categories of Continental Evolution and Quaternary Geology. The former include crustal accretion, intraplate tectonics, neotectonism and volcanism. Potential Quaternary Geology investigations include studies of fluvial, coastal and periglacial processes and glacial geology, as well as studies of the evolution and modification of climatogenic landforms that would help in reconstructing the climatic history of Alaska over the last two million years. In the southern part of the station mask there are also excellent opportunities for active volcano monitoring.

The highest priority objective of hydrology is to determine the magnitude of storages and fluxes of water in all its states and phases on the Earth's surface and its role in the Earth's biogeochemical cycles and atmospheric circulations. Additional objectives for hydrology, where SAR data would contribute significantly, are in understanding soil moisture and its movement, evapotranspiration and its role in regional climate, snow extent and condition, and extent of standing surface water. SAR data should also prove useful in initializing, updating and verifying the hydrologic components of the mesoscale and global scale atmospheric general circulation models.

The primary objective for terrestrial ecosystems research is the determination of the local, regional and global distribution of biomass and its controls and of gross primary production, respiration and nutrient cycling in terrestrial ecosystems. Also of interest are the quantification of the influence of changes in the land surface boundary condition on local and regional climate and vice-versa, and the determination of the role of land biota as sources and/or sinks of radiatively important trace gases. These objectives are global in nature, and ASF data in Phase 1 will permit research focused on a global context although the data are local as Alaska and Northwestern Canada contain extensive areas of boreal forest, tundra, peat lands, wetlands and coastal conifer forest. Each of these types of ecosystems provides a unique and important contribution to the global energy and mass budgets and their study will contribute to understanding productivity dynamics, land-surface interactions and biogeochemical interactions.

Another class of investigations discussed in this Plan falls under the general heading of remote sensing science. The main activity of remote sensing science is the study of the physics, biology and chemistry of Earth surface processes as they relate to the interaction of electromagnetic energy with the surfaces. This will be pursued through a combination of measurement and modeling studies performed in support of other research programs within NASA.

Interesting and useful scientific exploration is slated for the Alaska region using SAR data from ASF. Timely progress on these scientific endeavors requires appropriate developments and actions. First, a prelaunch research program is called for to optimize utility of the data in a timely way. This research must include a program to gather aircraft SAR images which approximately emulate ERS-1 data; they will be used by scientists to determine the sensitivity of C-band SAR data to geophysical phenomena. The research community has had too little experience with C-band data. Second is the refinement and automation of an algorithm to locate SAR pixels in Earth-fixed coordinates and with respect to pixels in other images, e.g. Landsat scenes, for change detection and multisensor applications. Third, the science programs call for image processing routines and systems in order to generate geophysical products from the data products. The SAR images are themselves intermediate products; they contain essential data on geophysical processes, but the generation and presentation of the data as information require sophisticated processing of the images. During the flight phase of the science programs will require specific, well-understood, accurate data products from ASF. Prompt action on these requirements is called for by the Prelaunch Science Working Team.

With these preparations, the ASF Program, including the highly capable Alaska SAR Facility ground station, the prelaunch research and preparation program and the image analysis capability to derive geophysical information from the SAR data, will make significant contributions to studies of global change and to the geosciences in the Alaska region. This opportunity is unique, and its timing fortunate, coming in the years immediately prior to the launch of the Earth Observing System (Eos). The ASF program will enable U.S. scientists and their international colleagues to prepare for Eos with both an excellent data set and powerful analysis tools. Thus, the focus of interest and energy on ASF will pay immense dividends. The time is right to push ahead on this program.

1. INTRODUCTION

Airborne and spaceborne Synthetic Aperture Radar (SAR) systems have already provided a great deal of information on the phenomena associated with surface processes. SAR data have proven useful in studies of sea ice, geology, glaciology, vegetation cover, soil moisture, surface hydrologic elements, snow cover, and oceanic features. Work with data from Seasat, which flew in 1978, confirmed the sensitivity of SAR data to the geometry of surface features and to changes in surface dielectric properties. Seasat was particularly successful in providing SAR data to investigations in sea ice, geology, and oceanography. The subsequent flights of Shuttle Imaging Radar-A (SIR-A) in 1981 and SIR-B in 1984 supported arid-region geomorphology research and terrain studies, the first radar study of ice in the Southern Ocean, and studies of ocean waves including the wave field produced by a hurricane. The utility of SAR derives from its all-weather and day-night capability, its fine resolution and its sensitivity to changes in the Earth's surface characteristics such as, for example, ice type, snow moisture and depth, rock morphology, soil moisture and plant canopy. The full development of the use of SAR data in geophysical investigations calls for routine observations of geophysical processes.

In recognition of the potential value of SAR data for Earth-science studies, a Science Working Group was established by NASA. In 1983 the Group published a discussion of scientific benefits of an Alaska SAR Facility (ASF) for acquiring and processing satellite SAR data as well as a preliminary list of science requirements for such a program (Weller et al., 1983). NASA subsequently appointed an ASF Science Review Group to monitor the initial development stages of the ASF with emphasis on system design approaches. More recently NASA appointed the Prelaunch Science Working Team (PSWT), composed of representative scientists from all the disciplines expected to use ASF data, to generate this Science Plan and to review the progress of the ASF implementation. The Science Working Group considered the application of SAR data to investigations in polar oceanography, geology, glaciology, ecology, hydrology, and oceanography. Opportunities for progress and the overall data needs were determined to be greatest in the area of polar oceanography, and consequently this discipline is considered the prime user of the ASF data. The choice of the University of Alaska at Fairbanks (UAF) as the receiving site affords optimum sea ice coverage, collocation with an active research program, and access to adequate maintenance support.

The ASF is a NASA project for the implementation of a facility for reception of spacecraft SAR data, a processing system for the generation of SAR images, an archive to support the science investigations and an operations system. The implementation of the receiving and data processing systems of the ASF Project is the responsibility of the Jet Propulsion Laboratory (JPL) of the California Institute of Technology, and the operations and science program administration are the responsibility of UAF. The antenna and processor will be capable of receiving and processing SAR data from the European Space Agency (ESA) First European Remote Sensing Satellite (ERS-1), the Japanese First Earth Resources Satellite (J-ERS-1), and the Canadian RADARSAT. At present Memoranda of Understanding have been signed between NASA and both ESA and NASDA (the National Space Development Agency of Japan) for ASF access to data from ERS-1 and J-ERS-1, and discussions are under way with Canada regarding a similar agreement.

While the initial utilization of ASF, to receive and process data from the ERS-1 in the Alaska station mask, shown in Figure 1, is focused on the study of local phenomena, the importance and relevance of the ASF extend well beyond the area of its station mask. Studies conducted within the station reception area are expected to make significant contributions to understanding of global processes and global change. This comes about because the high latitudes serve both as indicators of climate change, since the climate change is predicted to be largest there, and as sites of critical processes which influence the global climate. This global connection and its importance have been pointed out in national and international planning documents describing large-scale interdisciplinary programs including e.g. the IGBP (International Geosphere-Biosphere Program) of ICSU, the Earth System Science Program of NASA and the Global Geosciences Program of NSF.

The purpose of this Science Plan is to describe examples of scientific investigations in which significant progress can be made by exploiting ASF data from ERS-1 SAR images, to discuss the data products necessary to support those investigations, to outline the specialized prelaunch research necessary to develop requirements and algorithms for data-product generation, and to make recommendations on the optimum approach for the product generation. *Actual ASF science investigations will not be restricted by these discussions; all innovative applications of SAR data will be appropriate for investigation.*

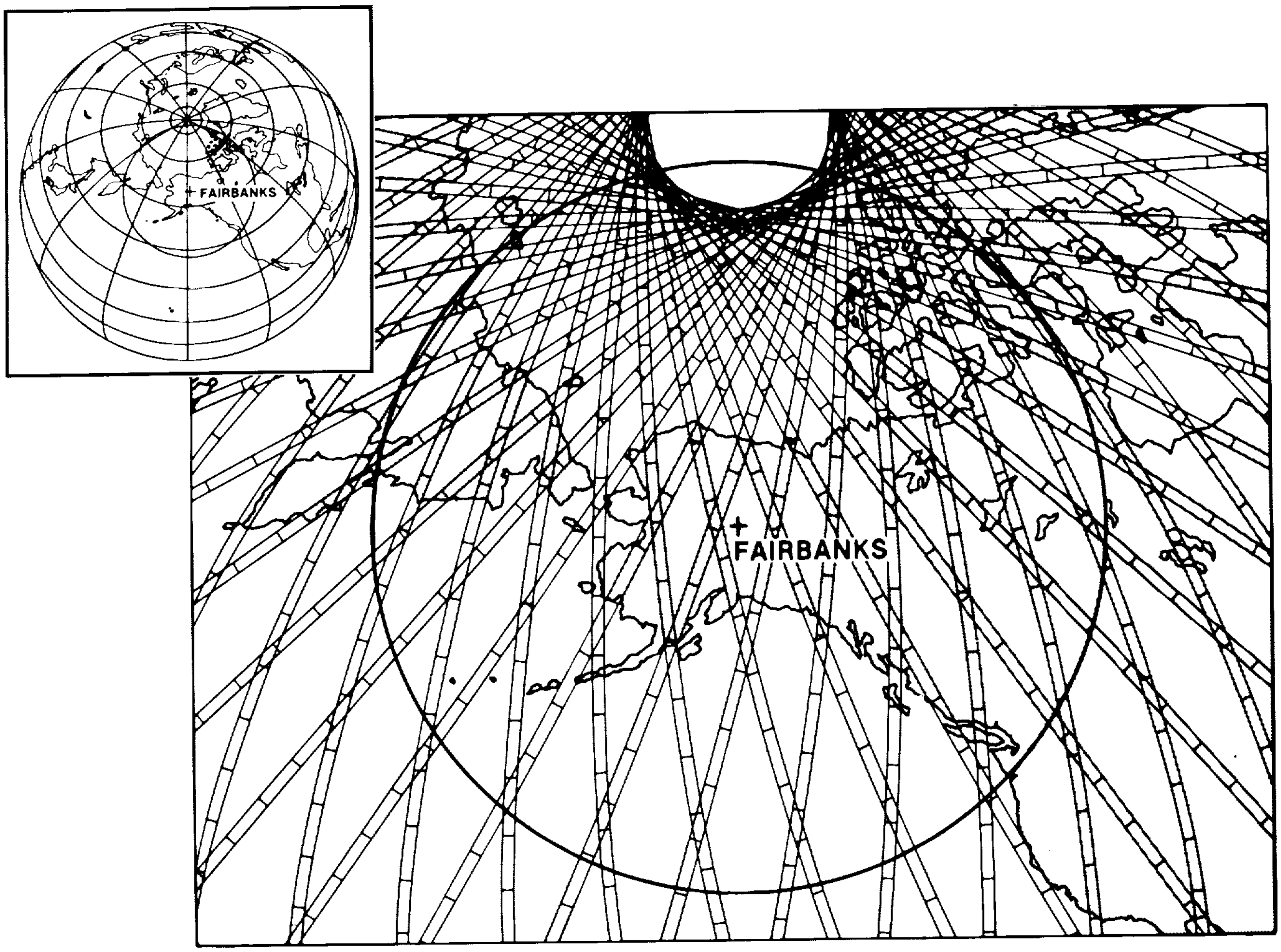

Figure 1. Alaska SAR Facility Station Mask

2. SCIENCE OBJECTIVES

Science objectives for specific geophysical discipline areas in which ASF data can be expected to make a significant contribution were reviewed by the ASF Prelaunch Science Working Team at meetings in Chena Hot Springs, Alaska and are presented below. There is considerable variation among disciplines as to the degree to which SAR data have been historically useful. In some disciplines, notably studies of sea ice dynamics, the application of SAR data is straightforward and well-developed, and the SAR-derived information is crucial to progress in the science. In other disciplines the interpretation of SAR images is more difficult or even ambiguous and in these cases the science objectives are more exploratory in nature. Still, SAR data promise to be of significant benefit in a large number of diverse branches of Earth science concerned with global-scale problems over the decade of the 1990s.

The following discussions on science objectives, opportunities and data needs for the ASF are organized to address polar oceanography, open-water oceanography, glaciology, geology, hydrology, ecosystems, remote sensing science and operational demonstrations. Oceanography is subdivided because the presence of ice significantly changes the objectives and system requirements applicable to the oceanography of the open seas. Remote sensing science is concerned with broad, fundamental issues in the application of satellite data to the study of various surface processes and tends therefore to be interdisciplinary. The goals of the planned applications demonstration program are (1) to identify areas where utilization of SAR data will significantly improve the information available to near-real-time operations, resource management and environmental monitoring programs, and (2) to encourage the research required to establish the applicability of such data to these areas.

2.1 Sea Ice and Polar Oceans

Before the flight of earth-observing satellites in the early 1970s, the growth, decay and internal motions of the great pack ice areas of the Arctic went largely unobserved. This situation changed with the deployment of passive microwave remote sensing systems on satellites such as Nimbus and DMSP. Although the resolution of these observations is relatively coarse (˜ 10-km or greater) they nevertheless monitor the seasonal changes in the ice edge location and the ice-type and open water distributions within the pack. However the detailed observations needed by the scientific community to understand many aspects of sea ice behavior are still lacking.

The observations made by Seasat clearly showed that SAR could satisfy this observational lack by providing fine resolution data (˜30-m) so that individual sea ice features such as pressure ridges and floe edges could be both observed under all weather conditions and tracked on sequential images. In what follows, the capability of tracking sea ice and determining ice type through the seasons is assumed, although this capability has not been thoroughly established at C-band and for the summer months; scatterometer and surface data are encouraging that these determinations can indeed be made with confidence.

Ice Circulation. The prime objective of SAR sea ice observations of the arctic is to monitor the circulation of the ice on the basic scales of interaction and deformation of the pack. At present the circulation patterns of Arctic sea ice are only known on the largest of scales and in the most general way at locations well removed from the coasts. SAR data will enable these patterns to be examined on a range of scales extending down to the floe scale as a function of meteorological and oceanographic conditions and ice type and thickness variations.

Heat and Mass Fluxes. Associated with recent emphasis on studies of the behavior of the earth as a system, estimates of heat and mass fluxes are key objectives of sea ice research. ASF data will contribute to improved estimates of the fluxes of heat and mass in the Arctic and, more important, to their role in the global climate system. The SAR data cannot directly sense either heat or mass fluxes. However, by monitoring ice motion and deformation, open water and thin ice formation in leads, and by combining these observations with meteorological observations obtained from satellites and buoys, estimates can be made of ice growth rates, salt fluxes into the upper ocean and heat and moisture fluxes into the atmospheric boundary layer.

Momentum Fluxes. A related objective is the determination of the ice, oceanic and meteorological processes that exchange momentum between these three primary components of the environment. For this work the SAR data must be augmented by observations of the atmosphere and ocean. Also, a dedicated air-sea-ice modeling program is essential.

Rheology. Specification of sea ice rheology as it depends on location, season, ice thickness and ice type is an objective of ice study which is interesting in its own right and which is critical to understanding a variety of processes important in the interactions between the ice and its environment. SAR observations will contribute to the exploration of this problem by providing detailed information on the ice motion field and on the nature of processes occurring in the deforming ice pack.

Ice-Land Interactions. Specification is needed of the boundary conditions at the coastline and the detailed physics of ice-land interactions which involve the expenditure of pack ice energy in ridge-building and ice push as a consequence of seabed morphology grounding the ice and causing sediment plowing. These processes at the continental boundary significantly affect the behavior of the ice pack over the shelf where much of the oceanic heat loss occurs.

The Marginal Ice Zone. The description and evaluation of processes in the marginal ice zone are critical; here phenomena originating in the adjacent open ocean affect ice processes and oceanic fluxes. These processes include storm-generated waves, oceanic eddies and weather.

Air-Sea-Ice Modeling. Finally, SAR data will be useful in initializing, updating, and verifying the numerical models that are currently used in forecasting sea ice behavior. The adaptation of models to ingest this data is now under way.

2.2 Open Ocean

In the open-ocean areas within the station mask there are a variety of important oceanographic phenomena readily amenable to study via the use of SAR. These features include surface and internal waves, current and eddy fields, oceanic fronts, oceanographic effects resulting from local-scale atmospheric conditions, and surface effects resulting from both submerged topographic features and surfactants. ASF data should stimulate significant advances in the current understanding of these areas even though there is still no general consensus among the scientific community concerning many details of the interaction of SAR energy and the ocean surface. This optimism persists because ASF will provide the scientific community with long time series of observations of the radar return from the sea obtained under a wide range of environmental conditions; such a data set is uniquely conducive to testing hypotheses concerning the relative importance of various factors affecting the radar return.

Currents, Fronts and Eddies. Fronts and eddies are important circulation features occurring in the Beaufort, Chukchi and Bering Seas as well as in the Gulf of Alaska. SAR data should be useful in their study in combination with other satellite observations of these features. Changes in current systems should be sensitive indicators of global change.

Surface Waves. A prime objective of oceanography is the determination of the surface wave climatology. The directional spectra of the wave fields generated by the intense storms that frequently develop in the Gulf of Alaska and in the Bering Sea can be modeled and compared to wave estimates obtained from the ERS-1 SAR, scatterometer and altimeter. SAR also provides information on the propagation and attenuation of wave fields through sea ice near the ice margin.

Internal Waves. ASF data will contribute to the study of summer season energetics of the internal wave systems that occur over the Alaskan continental shelves; these waves are associated with the lenses produced by a combination of ice melt and river discharge.

Surface Expressions. Other research objectives that show particular promise include studies of the changes in shallow water topography and sea surface features, studies of ways in which SAR-derived information on the surface state of the sea can be utilized to provide fine scale information on surface wind fields and moisture fluxes, and studies of surfactant effects and of the spread of pollutants from both human and natural sources.

Oceanic Modeling. Finally, SAR data should prove to be useful in initializing, updating and verifying results of both ocean wave and ocean circulation models.

2.3 Glaciology

Glacier and ice sheet phenomena lending themselves to study via SAR observations fall into three broad areas of scientific and practical interest. First, there is the interaction between glaciers and climate; second, the dynamics of ice flow, and third, practical applications in engineering. Glaciers within the ASF station mask have been the major contributors to the rise of sea level observed over the last century (NRC, 1985), and they are principal candidates for intensive monitoring by spaceborne systems.

Glaciers and Climate. The prime objective in the study of glaciers and ice sheets with SAR is the evaluation of the interaction of the ice masses with the local and global climate. On the one hand, glaciers and ice sheets are the products of certain climatic conditions, and their changes, suitably interpreted, are sensitive proxy indicators of climatic change. On the other hand, glaciers influence climate in several ways, a spectacular example of which would be the outcome of the (possible) catastrophic breakup of the West Antarctic Ice Sheet. Easily observed indicators of glacier health, or mass balance, include changes in the surface velocity, the distribution of surface melt zones, iceberg production rates, and the positions of termini.

Dynamics. The second objective is to observe and model the movement of ice in the glaciers. The flow of ice in glaciers and ice sheets is a complex process involving three components: accumulation or ablation on the surface and base of the glacier, internal deformation of the ice itself, and sliding at the base of the ice. Catastrophic speed and margin position changes can be due to dynamic instabilities or boundary condition changes that bear little relation to climate. These processes must be studied to monitor climatically induced changes, and they are of great interest in their own right. Much can be inferred about glacier dynamics from sequential observations of surface flow features, of surface velocities, and of the positions of ice margins made on a variety of time scales, ranging from weekly to multi-annually.

Engineering. The evaluation of the engineering hazards of the glaciers and ice sheets is also an important objective. In addition to their effects on sea level, glaciers affect the lives of people who live near them. Their extent and changes have long influenced transportation routes and regulated water supplies in Alaska. Glaciers can also be hazardous, such as when they interact with active volcanoes or form ice-dammed lakes.

Glacial Geology. Finally, SAR imagery can, during the ERS-1 time period, make a major contribution to mapping of land surface features resulting from past glaciations in Alaska. This would provide input to the determination of past global climate change.

2.4 Geology

Geologic studies show that the Earth's terrestrial features have evolved over long periods of time in response to the combined effects of erosional forces at the surface and tectonic forces within the crust and mantle. The objective of geologic mapping and interpretation is to reconstruct the history of these dynamic processes and, in combination with stratigraphic, structural and other geologic and environmental studies, to learn more about the varied character and composition of the Earth and the history of its changing geologic environments. The high sensitivity of imaging radar to surface slope and the capability to observe and discriminate fine details of topography and surface roughness are powerful tools for observing land surface processes and for mapping geology in arctic and subarctic environments (Moore and Sheehan, 1981; Ford, 1984; Carver et al, 1985). Areas where ASF data should prove to be of considerable value include 1) Continental Evolution: the structure and evolution of accretionary terranes, intraplate tectonics, neotectonics, and volcanism at active plate margins; 2) Quaternary Geology: fluvial, coastal and periglacial processes, glacial geology, and paleoclimatic history; and 3) volcano monitoring. Also, terrestrial SAR data can serve as analogs for comparative planetology studies.

Continental Evolution. The primary objective in Continental Evolution is to understand how continents grow, evolve and break up in response to tectonic processes through time. The Alaska region provides excellent opportunities to study crustal accretion, intraplate tectonics, neotectonism and volcanism in a variety of tectonic environments including, in particular, a convergent plate margin.

Quaternary Geology. Important investigations in Quaternary geology include studies of the evolution of climatogenic landforms and relationships to glacial and interglacial events. Potential investigations include glacial and periglacial processes, coastal and fluvial studies, and evidence of long-term climatic trends.

Coastal Erosion. A related interdisciplinary objective is the determination of the dynamics of wind-forced motion of fast ice in shallow water which results in bottom scouring by ridge keels. Also, ice moving along and/or onto the beaches is an important factor in coastal erosion and stability and in sediment and pollutant transport. This subject is also of importance to ice processes in the waters of the continental shelves where most Alaskan shipping and economic development take place.

Volcano Monitoring. Determinations of the frequency of eruption and the rate of growth of volcanoes in the Cook Inlet area and the Aleutians are required to better understand these processes in the past. These eruption rates are also required as input for global climate models which are sensitive to the rate of continuous introduction of volcanic products into the atmosphere.

2.5 Hydrology

While the concept of the hydrologic cycle is familiar to every natural scientist, our knowledge of the magnitude of storages and fluxes of water on the Earth's surface is poor, especially at regional and global scales. Therefore, the goals of NASA's hydrology program are to better understand the storages and fluxes of water in all its states and in all its phases in the hydrologic cycle as well as the role of hydrology in the Earth's biogeochemical cycles. Remote sensing is the only feasible means by which the large-scale spatial variability of hydrologic processes may be investigated. Snow extent and characteristics are also important indicators of climate change, and they directly affect the climate through albedo changes. The annual range of albedo in the snow transition zone, separating snow-covered from snow-free areas at any particular season, is large, and the long-term variability of the location of this zone is a critical climate indicator which must be monitored. Permafrost is expected to undergo similar changes in distribution and characteristics as a consequence of climate change.

At microwave frequencies the scattering properties of soil and vegetation are controlled by their roughness and dielectric properties. The dielectric constant of water is 80 and of dry soil and vegetation is 2-3. Therefore the moisture status of soil and vegetation strongly influences the dielectric constant and consequently controls the radar scatter properties.

Soil Moisture and its Movement. The primary objective in using SAR data is to quantify the extent and amount of soil moisture and shallow ground water which comprise the short-term storage phase in the hydrologic cycle. (Although when this water freezes, storage times can be much longer - centuries in areas where permafrost forms.) Soil moisture determines how a basin responds to a precipitation event, and the chemistry of surface water is determined largely by reactions in the soil moisture zone. Knowledge of soil moisture content is also necessary in regional estimates of infiltration and surface runoff.

Evapotranspiration and its Role in Regional Climate. A key objective is the estimation of evapotranspiration fluxes which comprise the water movement from the surface to the atmosphere; these fluxes are characterized by spatial and interannual variability and are a major source of uncertainty in basin water balances.

Snow Extent and Condition. Estimation of area, condition and the water equivalent of the seasonal snow cover is a vital objective as it is the largest contributor to the water supply in middle and high latitudes. Major variables that affect the hydrologic and climatic role of snow are its water equivalent, its liquid water content, its albedo, and its areal extent.

Standing Surface Water. Areas of standing water and saturated soils are potential locations of anaerobic processes at the Earth's surface and are thus important sources of methane, a critical gas in the Earth's biogeochemistry.

Permafrost. Detection and mapping of permafrost areas and permafrost features with SAR data would be a significant advance in the study of frozen ground. The use of SAR to locate frozen ground has been proposed, and the identification of permafrost terrain through this and other means including the monitoring of indicator vegetation and geomorphic features would also be valuable.

2.6 Ecosystems

Ecosystems science attempts to understand plant processes and pattern dynamics of ecosystems by understanding the interrelationships among biospheric, atmospheric and lithospheric systems. Four major goals, which must be met to understand these interactions, have been identified by the Earth System Science Committee (ESSC, 1986; 1988). These are (1) To understand the primary biogeochemical cycles of the planet, (2) To understand the relation between climate and biota, (3) To understand the annual cycle and spatial distribution of primary production and respiration, and (4) To understand the controls on spatial distributions of biota over the surface of the Earth. In this context several broad research areas can be recognized that are appropriate focal points for ASF Phase 1 activities. These are land plant productivity, biogeochemical cycles, biospheric-atmospheric interactions and land surface interactions.

Land Plant Productivity. The objective of the study of land plant productivity is the determination of the global distribution of biomass and the controls on its heterogeneous distribution in space and its change with time. Also important is the determination of global distribution of gross primary productivity and respiration by autotrophic and heterotrophic organisms and the annual cycle and interannual variation of these processes.

Biogeochemical Cycles and Trace Gasses. The objective is understanding the biogeochemical cycling of carbon, nitrogen, phosphorus and sulfur. As part of that overall goal, specific objectives include the quantification of the global distribution of tropospheric gases by determining the strengths of their biogenic sources and sinks and by determining the role of land biota as sources and/or sinks of carbon dioxide and other radiatively important trace gases.

Land Surface Interactions. The objectives related to land surfaces are to quantify the interactions involving the vegetation, soil and topographic characteristics of the land surface and the components of the hydrologic cycle. Of particular concern is the quantification of the influences of changes in land surface evaporation, albedo and roughness, as mediated by the vegetation cover and its dynamics on local and regional climate.

Biosphere-Atmosphere Interactions. The key objective is the quantification of interactions between the vegetation-canopy boundary layer and the atmosphere. This research involves an understanding of canopy characteristics and exchange processes of gases, water and energy at this interface.

2.7 Remote Sensing Science

The primary objective of the Remote Sensing Science Program is to understand the details of the physics, biology and chemistry of processes that influence the electromagnetic properties of Earth's surface. This is accomplished through a combination of measurement and modeling studies in the optical, thermal and microwave regions of the electromagnetic spectrum in support of the geoscientific research programs. Remote sensing science also addresses sensor calibration studies. These activities, along with the development of algorithms, will play an essential role in deriving surface and near-surface geophysical information from SAR data.

2.8 Global Change

The oceanographic, geophysical, and ecological processes at work in the arctic and subarctic are important elements of what has been referred to as the Earth System. In many cases the arctic elements of this immense system and its varied interactions are both vigorously dynamic and highly sensitive to changes in the Earth System. Most of these interactions are poorly understood, and their study is of high priority (UCAR, 1988). Together these observations should provide an early indication of global climate change, predicted by numerical models to be largest in the polar regions. Studies of the interactions between the various components of the system are also crucial in understanding this global change since the polar interactions will significantly influence the entire global system (Barry, 1982; Weller et al, 1983; 1988). Similarly, study of the region's past climates will aid the understanding of past global climate changes, processes and responses.

Snow Extent and Character. The latitudinal extent and the characteristics of snow are important indicators of climate change; snowcover also directly affects the climate through albedo changes which are, in the transition zone, among the largest seasonal albedo changes on the Earth's surface.

Glacial Melt and Sea Level. The mass balance of the glaciers is of major consequence and must be monitored. Changes in mass balance of glaciers within the ASF reception area are believed to be a major contributing factor to the current observed rise in sea level (NRC, 1985).

Sea Ice Extent and Thickness. The extent and thickness of sea ice has been predicted as a major element affecting the climate change associated with greenhouse warming; these properties should be closely monitored. Feedback processes associated with sea ice amplify climate change and affect the entire global system (Parkinson, 1989).

Current Systems. Changes in the current systems of the North Atlantic, the Gulf of Alaska and the Bering Sea have been observed in conjunction with El Nino-Southern oscillation events, and may also characterize other global-scale climate fluctuations. Their local effects are unknown.

Permafrost Extent. The extent and thickness of permafrost terrain is also predicted to be very sensitive to climate change; it must be monitored and studied, and SAR data will be useful in mapping this frozen terrain and in indicating locations for on-site examination.

Boreal Forest Cover. The coverage of boreal forest and the health of the selected indicator species should be closely observed as these plant communities are not only sensitive to climate change but are themselves important agents in carbon fixing. The changes in latitudinal timberline should likewise be monitored.

Coastal Stability. Erosion and accretion of the coast should be monitored as a reflection of natural and man-made (e.g. sea level, pollutants) changes occurring both offshore, e.g. in the ice regime, and inshore, e.g. the permafrost or hydrologic regimes.

Volcanic Eruptions. The infusion of particles and gases from volcanic eruptions are known to strongly impact global radiation balance.

2.9 Applications Demonstration

The Applications Demonstration Program (ADP) is integral to the science program as the link between basic science and applications. It seeks to identify areas in which the SAR data show promise of application, based upon the first-hand involvement of the potential user community and the capability of the SAR data to meet those needs. Similarly, it will assist in the continued development of the science program as a source of information regarding the results of applications projects, the problems encountered, and subjects which require further research.

The objectives of the ADP are to encourage the utilization of SAR data in a variety of applications settings, such as those listed below.

Natural Events. The key objective of the application of SAR data is improved monitoring and forecasting of natural conditions or events, especially those that influence community safety or economic stability. These include monitoring snowcover and snowmelt, ice override at the coast, river-ice breakup, volcanic eruptions, catastrophic floods and the like. On the whole, observation of these events is also of scientific utility.

Resource Management. A secondary objective is to evaluate the potential of SAR data in the decision making process regarding management of agricultural, timber, fisheries and wildlife resources.

Environmental Disturbances and Trends. An objective of ADP is to explore the use of SAR data in detecting natural or man-made environmental disturbances, e.g. changes in hydrological balance or permafrost cover, and in managing the response to these.

Operations Support. A significant objective of this program is to test the utility of spaceborne SAR in assisting ongoing, time-sensitive operations such as transportation and offshore operations in ice-covered waters; airborne SAR has already established its utility in this area.

An example of an operational demonstration project using SAR data would be to monitor and model the development of the fast-ice cover along the northern coast of Alaska in support of planning safe, efficient over-ice transportation routes. Knowledge of the annual development of fast ice would enable state and federal agencies to regulate over-ice transportation, particularly for exploration activities, so as not to interfere with known wildlife migratory corridors or habitats. Examples of these projects are the monitoring of river channel morphology, the migration of braided streams for barge transportation and the distribution of fishing vessels within the 200-mile economic zone to help enforce federal fishery regulations.

3. MISSION DESCRIPTIONS

The three missions, ERS-1, J-ERS-1 and RADARSAT, have differences as well as similarities. Table 1 shows the overall SAR Mission descriptions of interest to the user scientist. While this Plan relates only to data from ERS-1, all the planned SAR satellites are shown in order to put the data from ERS-1 in chronological perspective and to aid in constructing coherent study plans over the next decade. Future publications will discuss the science opportunities and plans for the utilization of J-ERS-1 and RADARSAT.

TABLE 1: ASF MISSIONS

MISSION DESCRIPTIONS				
		ERS-1	J-ERS-1	RADARSAT
SAR	Frequency	C-band	L-band	C-band
	Polarization	VV	HH	HH
	Swath	100 km	75 km	50 to 500 km
	Resolution/looks	30 m/4	30 m/4	30 m/4-100 m/8
	Incidence	23 degrees	35 degrees	20-50+ degrees
	Orientation	Right	Right	Right
	Onboard Storage	none	about 10^{11} bits	about 10^{11} bits
Orbit	Inclination	97.5 degrees	98.5 degrees	98.5 degrees
	Altitude	785 km	568 km	790 km
	Repeat	3 days initially, then TBD	41 days	13 days
	Type	sun-synchronous	sun-synchronous	sun-synchronous dawn-dusk orientation
Mission	Launch	9/1990	2/1992	1994
	Lifetime	2-3 years	2 years	5 years
	Status	Approved	Approved	Approved in Canada, int'l collaboration pending
Other Instruments		Radar Altimeter, Wind/Wave Scatterometer, Along-Track Scanning Radiometer	Optical Sensor	none

3.1 ERS-1

The ESA First European Remote Sensing Satellite (ERS-1) is planned to launch from the Guiana Space Center in fall 1990. The launch vehicle will be an Ariane 4. The spacecraft will be placed into a sun-synchronous orbit with the initial orbit having a three-day repeat cycle. The ERS-1 mission is primarily oriented towards ice and ocean monitoring with an additional goal of obtaining microwave images of land and coastal zones.

The satellite core instruments are the Active Microwave Instrument (AMI) operating in C-band, the Radar Altimeter (RA), operating in Ku-band (13.7 Ghz), and the Along Track Scanning Radiometer (ATSR), a microwave and infrared surface-temperature radiometer from the United Kingdom. The AMI operates in one of 3 modes: image, wind or wave; the concern of ASF is with the image mode data. In this mode the incidence angle at swath center is 23 degrees, and the illuminated swath is 99 km wide at a distance of 294 km from the satellite track. The specified minimum swath-width is 80 km. The data from the AMI image mode will be processed at ASF, and the data from AMI in other modes and from the other ERS-1 instruments will be available to the scientific community through ESA Earthnet.

The ERS-1 is a three-axis stabilized, earth-pointed spacecraft. The spacecraft (payload and platform) housekeeping data will be downlinked through the platform S-band telemetry links. The payload telemetry data will be downlinked via two X-band channels. The S-band communications primary station will be located in Kiruna, Sweden. A mission management and control center (MMCC) will be located at ESOC (ESA Spacecraft Operation Center), Darmstadt, Germany. At least seven SAR stations are planned: Kiruna (Sweden), Fucino (Italy), Maspalomas (W. Africa), Gatineau (Canada), Prince Albert (Canada), Siowa (Antarctica) and Fairbanks (Alaska).

The mission phases for ERS-1 are pre-launch, launch and early orbit (one week maximum), commissioning (three months minimum) and routine (two years nominal and three years goal). The launch and early orbit phases begin with launch and terminate with the spacecraft in the nominal orbit, with antenna and solar array deployment complete and in the nominal attitude control mode. During the routine phase, the ERS-1 system will demonstrate its potential as an operational system providing users with the desired data products.

3.2 J-ERS-1

The J-ERS-1 spacecraft is scheduled to be launched by an H-1 vehicle from the Tanegashima Space Center in February 1992 into a sun-synchronous orbit. The main objectives of the J-ERS-1 mission are (1) to establish the technologies of active microwave and optical sensors, specifically the Synthetic Aperture Radar (SAR) and Optical Scanner (OPS) and (2) to examine the terrestrial resources and environment, primarily focusing on geological and topographical surveys as well as other applications such as improved scientific understanding of snow cover, sea ice, sea surface temperature, and vegetative distribution, support for increasing development of coastal and offshore activities, and observations related to environmental pollution on a global basis.

J-ERS-1 is scheduled to carry an active sensor, a passive sensor and a mission data recorder. The first sensor is the Synthetic Aperture Radar (SAR). The second sensor is the OPS, an optical scanner, with nadir scanning and stereo viewing capabilities in the visible and near infrared wavelengths. (The OPS bands are 1:0.52-0.60; 2:0.63-0.69; 3:0.76-0.86; 4:0.76-0.86 [forward viewing]; 5:1.60-1.71; 6:2.01-2.12; 7:2.13-2.25; 8:2.27-2.40 micrometers.) The forward-nadir combination in bands 3 and 4 is for stereo viewing with an angle of 15°.

J-ERS-1 will utilize a box-type bus. Its total weight will be approximately 1400 kg with characteristic dimensions 3.5 x 1.8 x 1.6 meters for the satellite body carrying a 12-meter length SAR antenna. The design mission life of J-ERS-1 is two years after launch. The L-band SAR will provide data with approximately 18-meter spatial resolution over a 75-km swath width. The antenna off-nadir angle will be 35 degrees. SAR image data as well as OPS data will be downlinked via two X-band carriers. The J-ERS-1 orbit is designed to view, with both instruments, 100% of the earth in about 5 repeat-cycle periods, or about 220 days. Thus, the satellite lifetime will permit at least 2 such mapping exercises.

The J-ERS-1 mission management organization is located at the Hatoyama Earth Observation Center which is responsible for mission management and, in particular, for scheduling, data acquisition and processing in accordance with the requests of domestic and foreign users. The Data Receiving and Processing Facility at Hatoyama is responsible for reception, processing, archiving, and distribution of image data.

3.3 RADARSAT

The RADARSAT Program has gone through several significant modifications since its inception in 1980. The program is now primarily Canadian with the US as a junior partner supplying the launch and participating in the science program. The RADARSAT spacecraft is now scheduled to launch by the NASA-supplied Delta-type launch vehicle in 1994. The satellite will be placed in a sun-synchronous dawn-dusk orbit at an altitude of about 790 km. The orbit selected has a 16-day exact repeat cycle containing a three-day near-repeat subcycle.

The only instrument the satellite carries is a SAR which is capable of an extensive range of operating modes including the steerable basic mode with incidence angles from 20 to 49°, experimental modes at higher angles, and ScanSAR modes with a maximum swath width of 500 km at about 100 m resolution. In order to map the Antarctic continent at fine resolution for the first time (using any sensor), the satellite will be capable of rotating itself to orient the SAR antenna left for a few days and then returning to its normal configuration.

RADARSAT has a high rate data link consisting of two 100 Mbps X-band channels. There are to be at least three SAR data acquisition facilities including the Alaska SAR Facility, Fairbanks, Alaska and the two RADARSAT sites, the main facility at Gatineau (near Ottawa) and a second station at Prince Albert, Canada. Other receiving stations may be added as international agreements for data are negotiated.

The SAR receiving and processing facility at Gatineau will produce a full range of products including near-real-time imagery for support of operational agencies in Canada.

4. THE ALASKA SAR FACILITY

4.1 Background

The Alaska SAR Facility, or ASF, was conceived and proposed as a vehicle to support innovative scientific studies involving imaging radar data, in particular studies of sea ice dynamics of the Arctic Ocean and Alaskan waters. The basic overview of the ASF program is shown in Table 2. The ASF program consists of a facility at Fairbanks and a science program, coordinated by UAF, for the management of the research investigations. The ASF will consist of a Receiving Ground Station (RGS), a SAR Processing System (SPS), and an Archive and Operations System (AOS). The AOS is further subdivided into an Archive and Catalog Subsystem (ACS) and a Mission Planning Subsystem (MPS). A Science Working Team (SWT) will conduct research using ASF and other data. The RGS will be able to receive and record SAR signal data from ERS-1, J-ERS-1, and RADARSAT, but to date planning is complete only for reception and processing of ERS-1 data.

TABLE 2: THE ASF SCIENCE PROGRAM

Science Goal
Support, with data from European, Japanese and Canadian spacecraft, scientific investigations of air-sea-ice interaction, open-water oceanography, geology, glaciology, hydrology and ecology; initially these studies will be restricted to the Alaska station mask, but in the later phases they will become global.
Overall Approach
Establish and operate a SAR receiving, processing and analysis facility at Fairbanks to supply SAR image and geoscientific data.
Select a Science Working Team for full exploitation of the SAR data.
Coordinate SAR data needs between the Science Working Team and the flight agencies.
Communicate summary research findings to the flight agencies, to NASA and to the scientific community.

The SPS will process the SAR signal data into various image formats. These include a low resolution image suitable for some geophysical analyses, a full resolution image similar to the SAR images obtained by Seasat and the SIR missions, and a 1-look complex image of the finest possible resolution for specialized analysis. The SPS will supply the image data to the AOS which will archive and catalog the images and will also supply image products to the SWT. Each of these major ASF components will be discussed in greater detail in the sections that follow. The SWT will conduct the research program, advise ASF on science requirements, and communicate ASF results to the scientific community through publications and presentations. It will also provide advice in developing an Applications Demonstrations Program. The SWT membership will be augmented when called for by changes in the ASF data coverage or other factors. For the period prior to launch, a Prelaunch Science Working Team (PSWT) has been chosen consisting of representative scientists from the disciplines expected to benefit from ASF data. The function of the PSWT is to initiate science planning for the ASF Program. Prior to PSWT selection a Science Review Group served to advise the ASF Task Scientist.

4.2 Science Requirements for the Facility

The ASF system requirements imposed by the anticipated science program are shown in Table 3 and specified in detail in Appendix A. These have been drawn from the Report of the Science Working Group (Weller et al, 1983) which in turn utilized the Bilateral Study Team Report (Carsey et al., 1982). Additionally there have been refinements taken from the scientific literature published after the Science Working Group report (e.g. Curlander et al, 1985; Thorndike, 1986b) and from the PIPOR Group report (1985). (The Program for International Polar Oceans Research (PIPOR) Group, was established by NASA, the Canada Centre for Remote Sensing (CCRS) and ESA to review the application of satellite data to high latitude oceanography.) The requirements for ASF were further reviewed by the NASA-appointed ASF Science Review Group in meetings in November, 1985 and October, 1986, and revisions to the Archive and Operations System requirements were made in response to their comments, contained in a letter to NASA and forwarded to ASF.

TABLE 3: SCIENCE REQUIREMENTS: ALASKA SAR FACILITY

Program Requirements
A Receiving Ground Station to collect and record data from ERS-1 of ESA, the ERS-1 of NASDA (Japan), called J-ERS-1, and to be readily upgradable for RADARSAT of Canada
A SAR Processing System to produce timely and accurate SAR images from the spacecraft data
A Science Working Team to conduct investigations with the SAR data and to implement analysis software for the generation of scientific information from ASF images
An Archive and Operations System to catalog, archive and provide SAR and geophysical data to the Science Working Team and to perform mission planning for both SWT and ASF Operations
Organization of prelaunch science program requirements including those for the design and proposal of field work in the prelaunch and postlaunch periods, for the definition of the Geophysical Processing Systems, and for other necessary research

4.2.1 Data Required

The key data issues for most disciplines are: 1) The tradeoff between frequency of repeat and the capability of mapping coverage and 2) SAR data quality including both geometric and radiometric properties and transformations.

The scientific areas which will be supported by ASF data generally require repeat-coverage data. In the case of sea ice studies the data can come from near-repeat orbits and still provide information on ice kinetics, especially if the repeat data is from orbits that "drift" in the same direction as the ice. Repeat intervals for ice studies should be on 2 to 6 day intervals; 3 day intervals used during Seasat are ideal. Oceanographic studies generally do not require repeat data except for those involving tidal currents. In hydrology repeat data is required for studies of changes in snowcover extent and condition, standing water and soil moisture. In ecosystems studies of areas of changing water level, a rapid repeat cycle allows monitoring of wet and dry soil cycles; the monitoring of these cycles is necessary for the modeling of the decomposition of complex carbon compounds for microbial bacteria. Other repeat requirements for ecosystems, such as those for forest studies, are on longer time scales. Geologic studies do not have a strong data repeat requirement except for the case of active volcanoes. Glacial studies will require repeat data on rather long time scales, e.g., weeks to months. For both geologic and glaciological studies there is a requirement for mapping of large areas requiring long-repeat orbits which must be planned in such a way as to insure access to the several-day repeat called for by most of the investigations.

4.2.2 Type of Image Products

Full resolution (30 m) data are required for most terrestrial applications. Examples include most mapping experiments as applied to tectonics, ancient drainage systems, cold-regions geomorphology and topography. Full resolution is preferred in hydrology for wetland studies and in glaciology for observing and monitoring fine details of glacier features (cf. Shuttle Imaging Radar-C Science Plan, 1986). Limited one-look complex images will be required for special studies that rely on high resolution and/or speckle analysis. For maximum utility in many experiments in geology and hydrology, images should be geocoded to standard map projections and radiometrically calibrated. Terrain-corrected ERS-1 data are necessary for multisensor and multitemporal data coregistration and analysis. Stereo analysis is an important technique for some studies, but terrain-corrected SAR data cannot be used for stereo combination with other image data. Both terrain-corrected and range-mapped ERS-1 data should be produced and archived for scientific analysis.

4.2.3 Calibration Accuracy

For most SAR geophysical applications, a relative radiometric calibration within +/- 1 dB is required over the duration of the mission. This calibration is required to supply adequate signal contrast over time and space and to permit automatic data analysis. Absolute calibration is less essential; the absolute signal level from known targets can be used to generate look-up tables that should be generally adequate to meet the requirements for absolute calibration. In some disciplines, however, there may be difficulties associated with the use of absolute calibration. The basic procedure is to examine an area simultaneously with surface-based scatterometers and spaceborne SAR. In some situations, e.g. snow hydrology, the spatial variations within a snowfield may render this comparison insufficiently sensitive compared with the signal levels involved.

Radiometric fidelity across the swath is also critical for some investigations. Radar returns from geologic surfaces extend over a dynamic range up to 20 dB. Radar backscatter measurements by Blom et al (1986) show that separability of recent lava flows at C-band is possible using calibrated data. For geologic mapping-mode experiments, it is important that the radiometric fidelity be as uniform across the swath as possible. For most ecosystem scenes the dynamic range of radar backscatter seldom exceeds 10 dB and is often less than 6 dB. It is therefore important that system-related variations within a frame and between frames be confined to less than 1 dB. Relative or absolute calibration has been shown to be essential in order to evaluate the responses of orbital SAR data to the full range of soil moisture conditions (Dobson and Ulaby, 1986).

5. SCIENCE OPPORTUNITIES

SAR data from satellites to fly in the early 1990s can significantly contribute to studies in the geosciences such as oceanography of open and ice-covered seas, geology, glaciology, ecology, and hydrology. These data will also be invaluable in detecting and examining global climate change. The research problems and opportunities discussed below are examples drawn from the scientific literature and not an exhaustive compendium; it is expected that new, innovative applications of this observational tool will be forthcoming as a direct consequence of the ASF Program.

Oceanic applications of SAR data are subdivided into two categories, those involving the ice-covered seas and those involving the open ocean. This separation is necessary because both the scientific objectives and the geophysical analysis techniques are distinctly different in these two areas. For ice-covered seas, SAR images can be used to describe the type of ice present on the surface and how it moves and changes with time. For the open ocean, SAR images respond to the intensity of short gravity waves on the surface, and the occurrence and strength of these waves is interpreted to infer current, internal wave, and surface wave field properties.

The 3000-km radius of the ASF reception area, or mask, shown in Figure 1, will cover all of Alaska and thus enable further studies of the land and of land surface processes over large, inaccessible areas. The application of SAR to problems in geology, hydrology and terrestrial ecosystems in remote areas is enhanced by the ability of the system to obtain data under all weather and lighting conditions. This is a great advantage in many regions of the Arctic where a combination of clouds, low sun angles and long periods of darkness severely reduce the effectiveness of optical sensors.

5.1 Sea Ice and Polar Oceans

Background. Data from spaceborne SAR systems, combined appropriately with in-situ data, other satellite data and results from numerical models, can greatly enrich our understanding of the influences of processes active at the surface of the ice-covered seas. Recently the polar regions have become of considerable interest because of their sensitivity to changes in the global climate system. The polar regions also serve as the global heat sink; in both the atmosphere and the ocean, heat is advected to the polar regions to be lost to space by radiation. Although the broad elements of this circulation are identified, many details of the mechanisms involved are still not quantitatively understood. Not only are the polar oceans unique among the world's oceans, they are also quite different from each other with the Arctic being an enclosed "mediterranean" sea (Aagaard et al., 1985) as contrasted with the Southern Ocean, which interacts strongly with the Atlantic, Pacific, and Indian Oceans (Carmack, 1986). In addition to the climatic roles of the polar oceans and their ice covers, they are also of interest because of variety of other reasons: the nonrenewable resources known or presumed to exist in the sedimentary rocks of their continental shelves and their importance as highly productive fisheries. Ice in the polar oceans can also act as a roadblock, impeding traffic across otherwise highly advantageous marine trade routes.

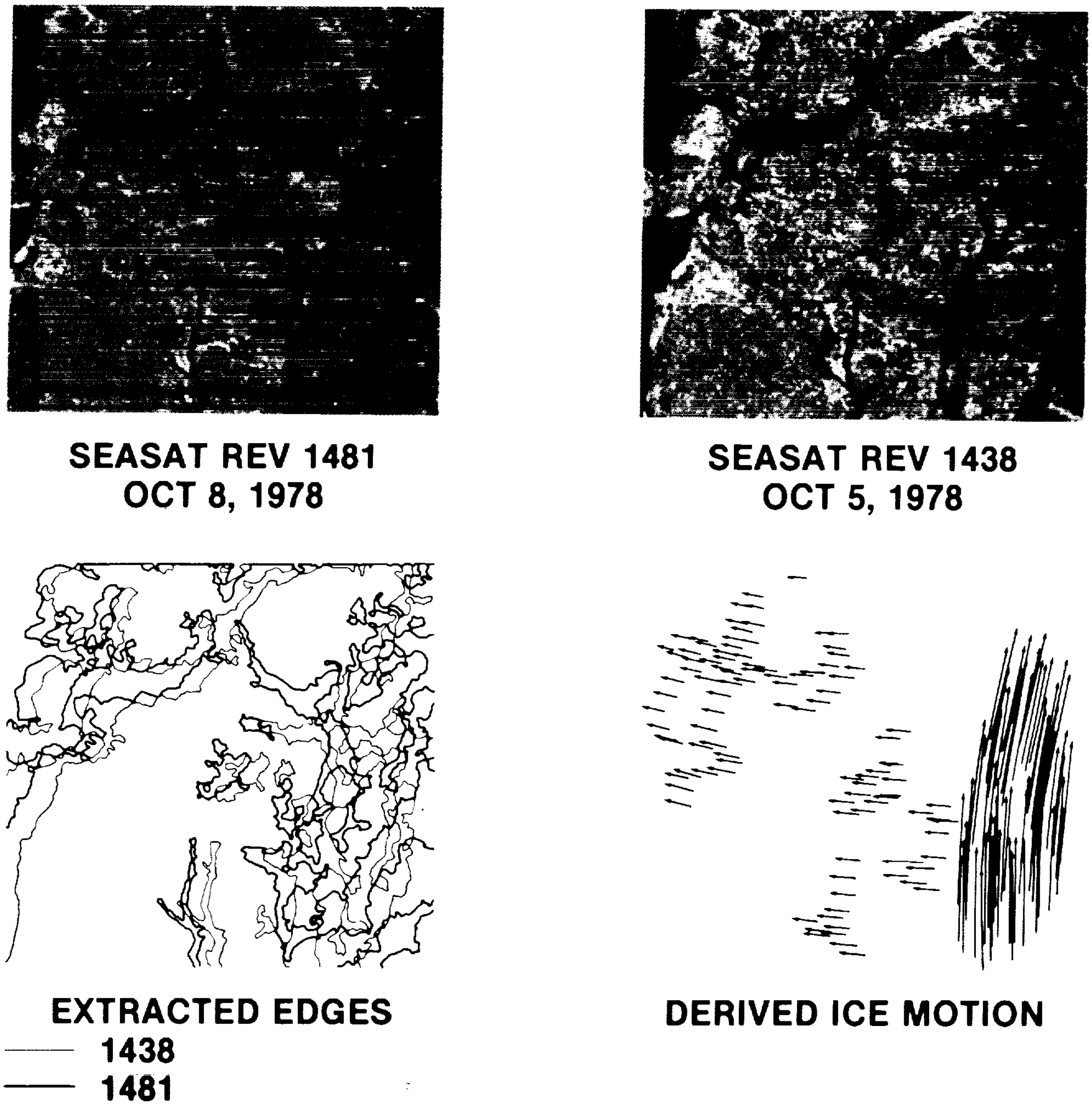

Figure 2. Ice Motion by Edge-Tracking. (Courtesy R. Kwok)

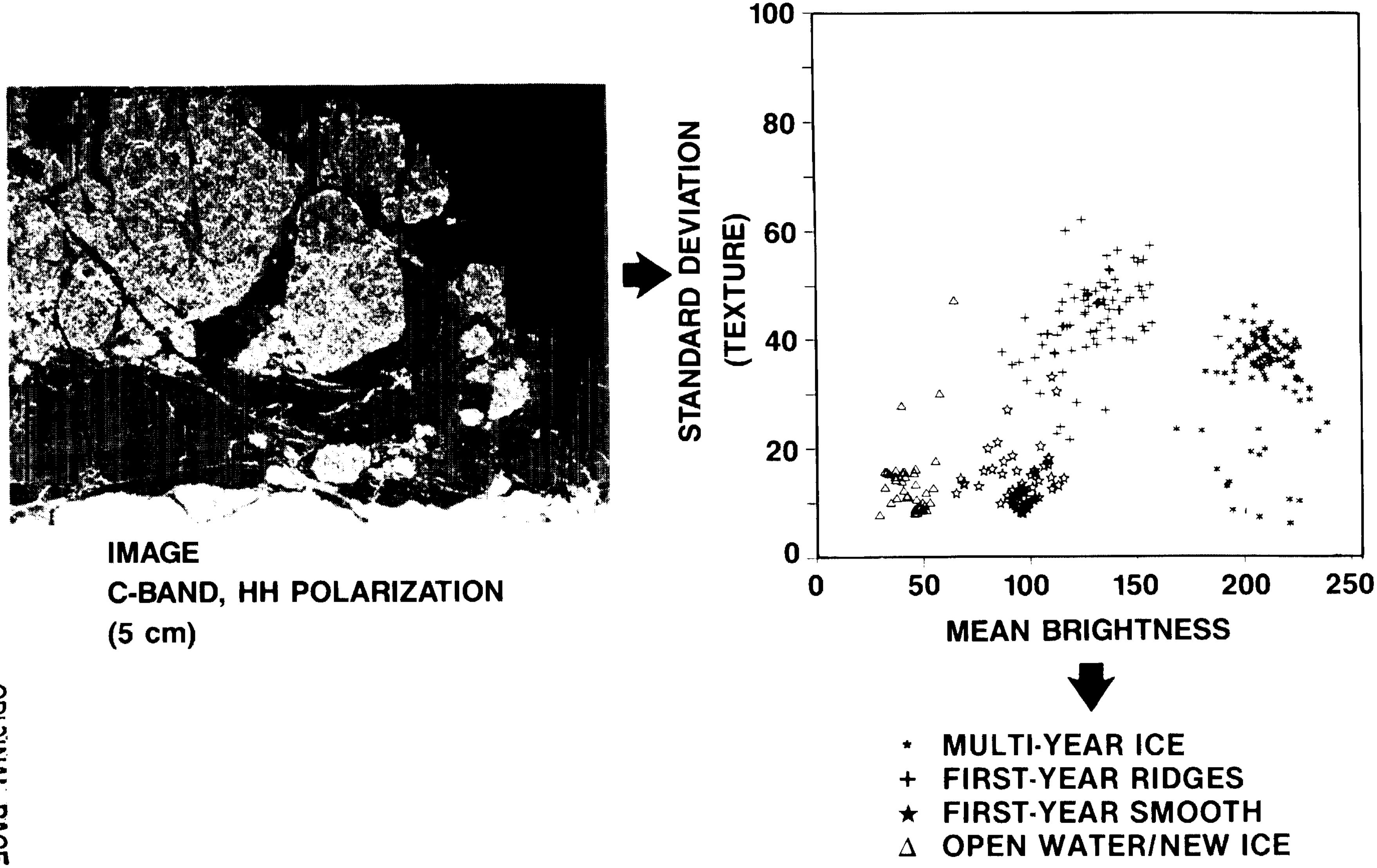

Figure 3. Ice Classification in Aircraft SAR Image. (Courtesy R. Kwok)

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It is increasingly clear that any adequate study of ice-covered seas poses demanding requirements as the observations must be spatially extensive and temporally frequent. Until recent times the variability of the ice cover itself was misunderstood because its local variability was strikingly at odds with global and regional variability (Walsh and Johnson, 1979). Because the critical phenomena of climatological interest are the air-sea-ice and air-sea-ice-land interactions driven by wind and current stresses and by thermodynamic processes, the observations themselves must be on the scales of major storms and circulation features. This demands, on one hand, coverage with a length scale of 1000 kilometers, a frequency of a few days and the ability to resolve feature motion of a few hundred meters and describe 30-km eddies. Due to the highly seasonal lighting conditions and the prevalence of cloud cover, visible light and infrared satellite observations are of limited value in these regions; active and passive microwave sensors must be used. In the past, extensive global-scale and synoptic-scale research has been accomplished with satellite-based passive microwave observational systems. Indeed, microwave observations obtained as part of the Nimbus program have greatly improved our understanding of variations in large-scale sea ice conditions (Carsey, 1982; Zwally et al., 1983; Parkinson et al., 1987). However, these observations are resolution-limited as many air-sea-ice interaction processes occur on scales that are too small to be resolved by passive systems with their 10 to 100-km resolutions. The observational technology needed to fill this gap is SAR.

SAR observations of sea ice provide information of the most fundamental type, the type of ice present and the nature of its motion and deformation. Figure 2 shows ice motion determined by automatic tracking of features in Seasat images, and Figure 3 shows an aircraft C-band SAR image of sea ice and the textural qualities of the ice types which enable their classification. A central topic of sea ice geophysics is the circulation of the ice and its mass balance in time and space. SAR observations can play a critical role in understanding these processes. SAR observations can also make major contributions to studies of processes occurring in the ice at locations near its boundary with the open sea, interactions between the ice cover and coastlines, unique features of the behavior of ice in marginal seas such as the Bering Sea, the dynamics and thermodynamics of polynyas in both the Arctic and the Antarctic, the processes occurring during the melt season, and information on the ever-changing floe structure of the ice itself.

Ice Circulation and Mass Balance. Nearly a century has passed since Fritjof Nansen demonstrated the existence of transpolar ice drift in the Arctic Ocean. In this circulation ice that forms over the Siberian continental shelves makes its way, over a several year interval, across the Arctic Ocean and ultimately through Fram Strait and the Greenland Sea to melt in the warmer waters of the North Atlantic. A quantitative understanding of the motion and mass balance of this great current of ice as well as of the Beaufort Gyre (a vast clockwise eddy located in the Beaufort Sea north of Eastern Siberia and Alaska and extending essentially to the North Pole) is a central problem for arctic glaciology and oceanography.

To date our knowledge of ice circulation in the Arctic Basin is based on the drift of manned ice floes and ice-island stations and in the recent past on positional data collected by drifting buoys placed on the ice (Colony, 1989). As might be expected, this information is irregularly spaced in both time and space, even including the recent buoy data. Particularly lacking is circulation information from regions covered by highly mobile seasonal ice covers which are equally inhospitable to ships, ice camps and data buoys. The great advantage of SAR is that it will reduce the number of buoys required and also provide observations from regions such as the marginal seas and the Siberian Shelf where it is difficult both logistically and operationally for buoys to be replaced and to survive. A number of questions turn on the matter of ice circulation. How much of the annual ice production occurs over the arctic continental shelves? How much ice forms within the slowly diverging central arctic pack?

What is the distribution of ice types within the pack and marginal seas? How much of the ice in the Greenland Sea and the other marginal seas forms and melts in one place?

Heat and Mass Fluxes. Another key problem is the specification of heat and mass fluxes for different regions of the Arctic for different times of the year. Although SAR cannot measure these parameters directly, it can provide observations necessary to their estimation. For example, SAR data can supply data on ice type and concentration, ice motion, the formation of leads, the dates of their refreezing, and the areal amount of ice that is deformed into ridges. Supplementing this with buoy data on near-surface air and ocean temperatures and wind speeds, it is possible to calculate ice growth rates, partial ice thickness distributions, average heat and mass fluxes into the atmosphere and salt fluxes into the sea (Maykut, 1986; Cox and Weeks, 1988).

The surface fluxes are largely controlled by ice thickness and concentration (the percentage of a given region that is covered with ice). Several studies have examined the annual, biannual, and regional variations in ice concentration and the statistical relationships between concentration and variables which are presumed to have at least partial control over them such as surface temperature and pressure (Walsh and Johnson, 1979; Comiso and Zwally, 1984; Lempke et al., 1980).

Ice Pack Morphology and Air-Ice-Ocean Momentum Transfer. The drift of pack ice is determined by the ice momentum balance--a balance between the winds and currents pulling on the upper and lower ice surfaces, the Coriolis force due to ice motion on a rotating earth, and ice stresses generated by floe-floe interactions. It is necessary to be able to specify appropriate average air-ice and ice-water drag coefficients. However, it is unrealistic to consider continuous direct on-site measurements of surface stresses, heat fluxes and atmospheric stability over the vast regions of the Arctic Ocean. These quantities must be predicted from the regional atmospheric surface pressure field and limited information about the surface conditions of the ice. SAR will provide information on both the intensity and the spatial distribution of surface roughness elements; this information can then be used for estimating the form drag associated with different ridge heights and types. Thus, SAR data will yield improved roughness parameters for ice dynamics modeling.

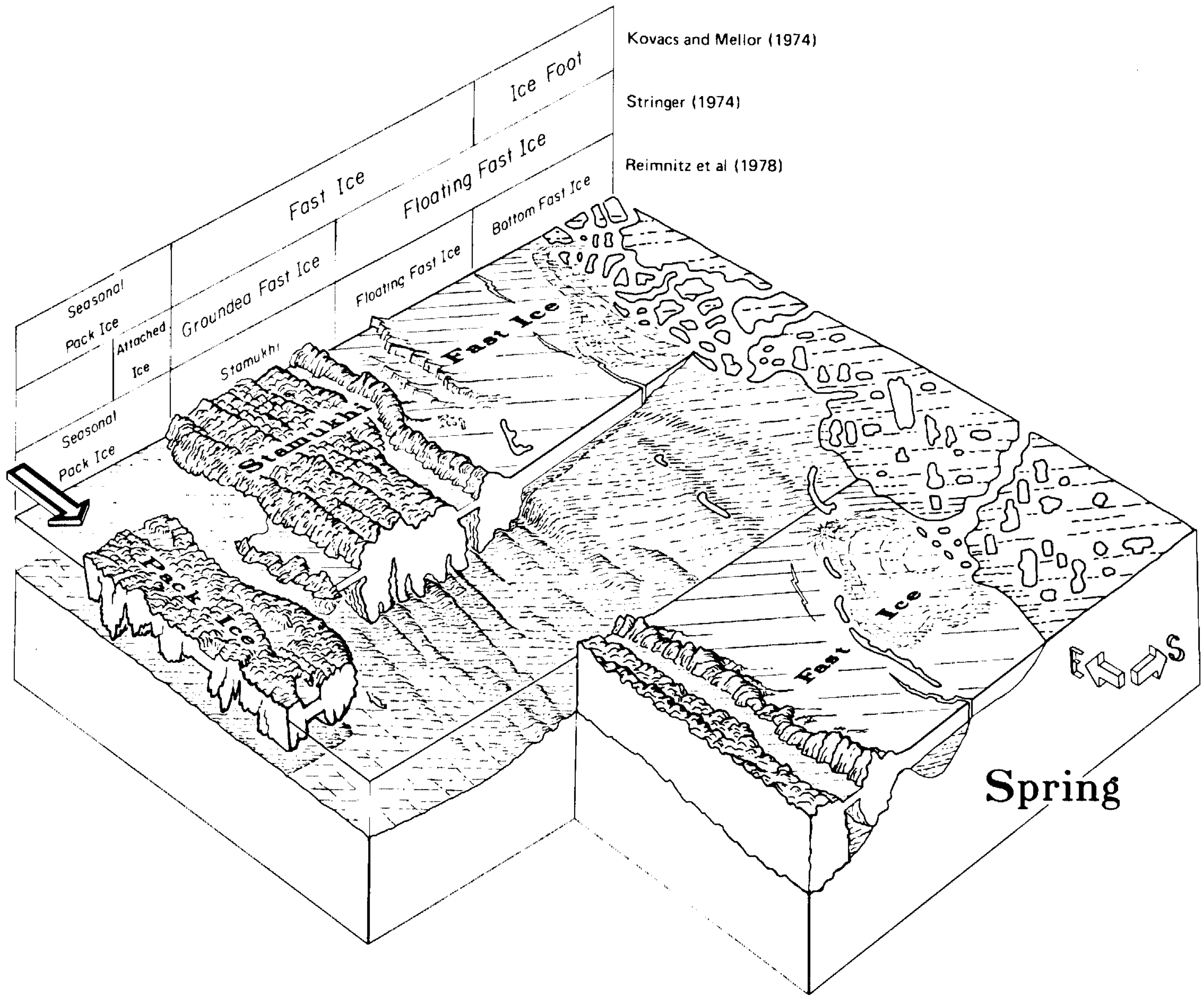

Figure 4. Schematic Diagram of Spring Beaufort Sea Fast Ice

Rheological Descriptions of Sea Ice. Theories of ice stress, expressed as constitutive laws which describe relationships between stress and strain, are used to describe the resistance of pack ice to deformation. In such formulations the stress is usually taken to depend on both the deformation or strain rate and on the ice conditions--particularly on the small fractions of the ice cover that are open water or thin ice (Coon, 1975; Hibler, 1980; Pritchard, 1988; Drinkwater, 1989). To date, the different formulations of such "laws" have been based on their physical reasonableness and computational ease, as direct tests of the effectiveness of alternate formulations have been difficult. Also, the observational demands for testing such laws are severe as they require accurate estimates of ice types occupying only small percentages of the total area. ASF SAR data will be a major improvement in observations of ice deformation, thin ice and open-water fractions; information that can be utilized to test which of the possible rheological models best simulates reality.

Air-Sea-Ice-Land Interactions. Near the continental boundary of ice-covered seas, interactions between the ice and the land influence the dynamics of the ice cover over the continental shelves. Here ice-ridging is most intense as the air-sea-ice interactions are constrained by drag along the coast and by ridge-keel drag along the sea-floor. The presence of the rough surficial ice canopy and the irregular seabed modifies the oceanic current regime as currents and tides are constrained by the shape and dimensions of the two surfaces. The continental boundary region is also the site for a substantial amount of the oceanic heat and salt flux reflecting freeze-up and river input processes. The boundary region is complex, involving grounded ridge keels, sea ice incorporation of sediments during frazil formation, ice push onto the coast, seafloor gouging by ice and ice-constrained currents. Figure 4 shows the configuration of the ice along a coastline including several different systems of nomenclature which have evolved to describe the ice cover. ASF SAR observations will provide time series data of the continental boundary ice zone to monitor the time, location and character of ice ridge formation in relation to bathymetry and to monitor conditions during the logistically inhospitable periods of freeze-up and breakup when boundary dynamics are probably most intense. These will be critical inputs to modeling of coastal and shelf ice dynamics.

Air-Sea-Ice Interactions in the Marginal Ice Zone. SAR provides an ideal technique for carrying out studies in the Marginal Ice Zone or MIZ in that it provides information on both the ice and ocean characteristics of primary importance in this extremely interesting region. In the marginal ice zone the mesoscale air-sea-ice interactions have associated horizontal processes which transport ice or warm water across frontal zones and associated vertical processes which transport heat, brine and momentum within the ocean. Figures 5 and 6 depict processes of the ice margin. Reference is made to the *Journal of Geophysical Research* special issue on Marginal Ice Zone Research (Muench et al, 1987). Detailed studies of such areas will require simultaneous measurements of the physical state of the upper ocean and lower atmosphere; ship or "smart" buoy data will definitely be needed.

Within the ASF station mask is the Bering Sea marginal ice zone, a particularly important area that shows strong interactions between the physical and biological components of the ocean (Niebauer and Alexander, 1985; Niebauer and Smith, 1988). In the spring the ice is melting and the atmosphere, ice and ocean environments are very dynamic, Major studies of polynyas in the Arctic and of the Saint Lawrence polynya in the Bering Sea in particular are planned as part of the International Arctic Polynya Project. SAR data from ASF will contribute an essential all-weather monitoring capability to the research. A satellite-borne instrument important to this program and to other multidisciplinary studies is the Sea Wide Field Sensor (SEA-WIFS) proposed for launch in 1991 to resume the ocean color measurements initiated by the Coastal Zone Color Scanner (CZCS) on Nimbus 7. These data, which will provide information on chlorophyll concentration and primary productivity, can be taken coincidentally with ASF SAR data. The resulting combined data set will be of critical value to a variety of projects studying the interaction of physics and biology in high latitude waters.

Ice Kinematics. Because ice stress and processes affecting mass and heat balance depend on spatial differences in the ice motion field, it is crucial to have a clear conceptual model and an accurate statistical description of the kinematics of sea ice. In short it is essential to be able to describe how sea ice moves as contrasted with why it moves (Thorndike, 1986). In the past, both models and interpretations of field data were based on the continuum hypothesis--namely that ice velocity was spatially differentiable. Observations from LANDSAT and SAR have shown, however, that the ice moves as rigid floes that may be up to tens of kilometers in dimension with deforming areas between these floes occupying bands that are only kilometers wide (Fily and Rothrock, 1987). The development and verification of such descriptions and models will help to clarify significant problems in data interpretation and handling, e.g., the best way to utilize the motions of a set of points to estimate mean ice deformation over large areas, and sizing errors to be anticipated in such estimates. The ASF SAR data can play a key role in advancing this area of study.

Sea Ice Modeling. In the face of insufficient data to support diagnostic studies of sea ice behavior, scientists have turned to numerical models to simulate this behavior (Coon, 1980; Hibler and Bryan, 1987; Walsh et al, 1985). Advances in this general area have been impressive, with models gradually becoming more and more sophisticated in their attempts to simulate reality. Unfortunately, as the details in the model predictions have increased, it has become more and more difficult to verify these predictions. SAR data has great potential for application in modeling research, principally in initializing and updating models. However techniques for inputting such data into these models are not currently available, although development of ingestion methods are underway in other fields, e.g., meteorology. Clearly the availability of SAR data will stimulate activity in this general area. The availability of SAR data for this purpose should assist ice dynamics models in achieving their full potential.

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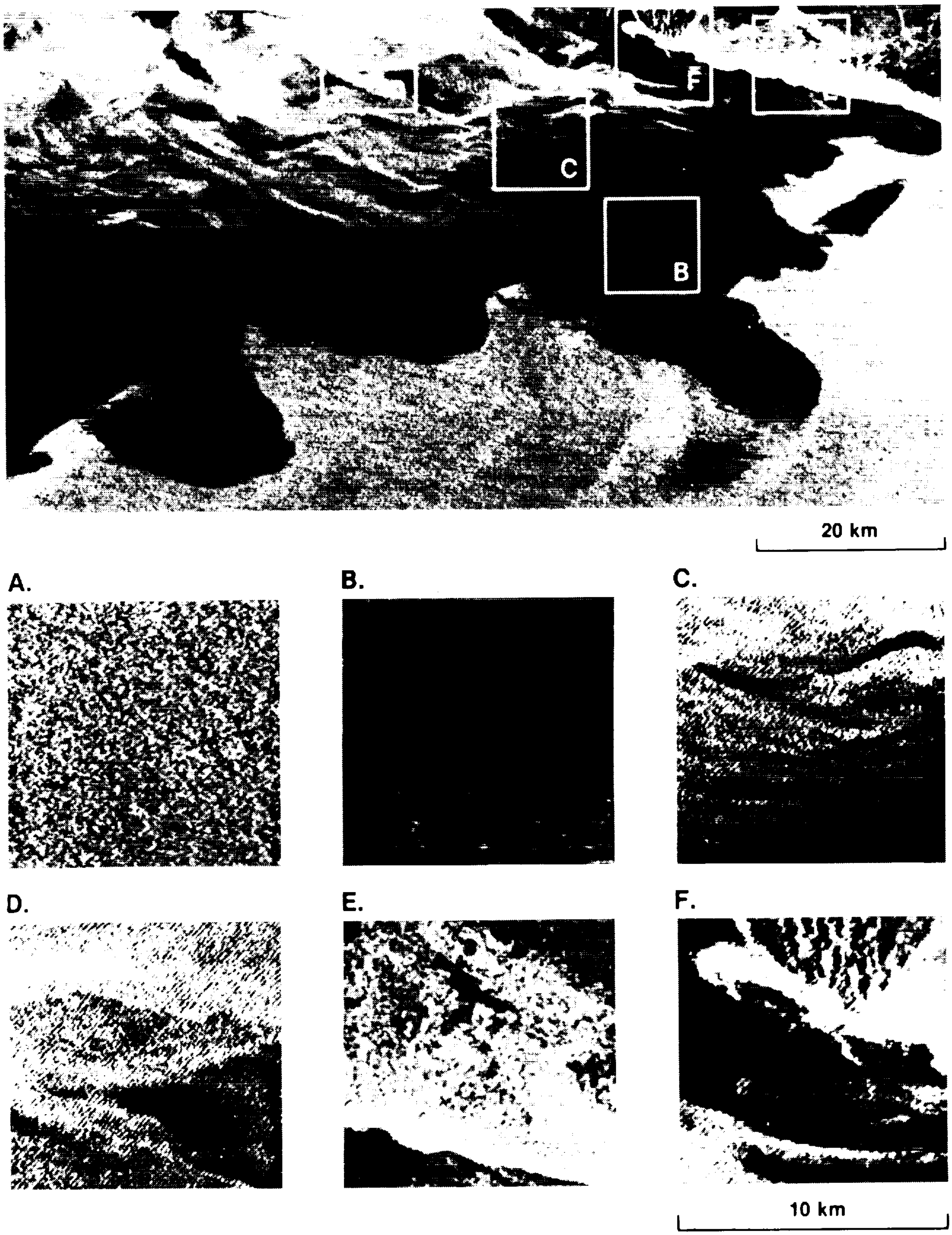

Figure 5. Seasat SAR Image of Swell in Beaufort Sea Ice Margin. (Courtesy of Ben Holt)

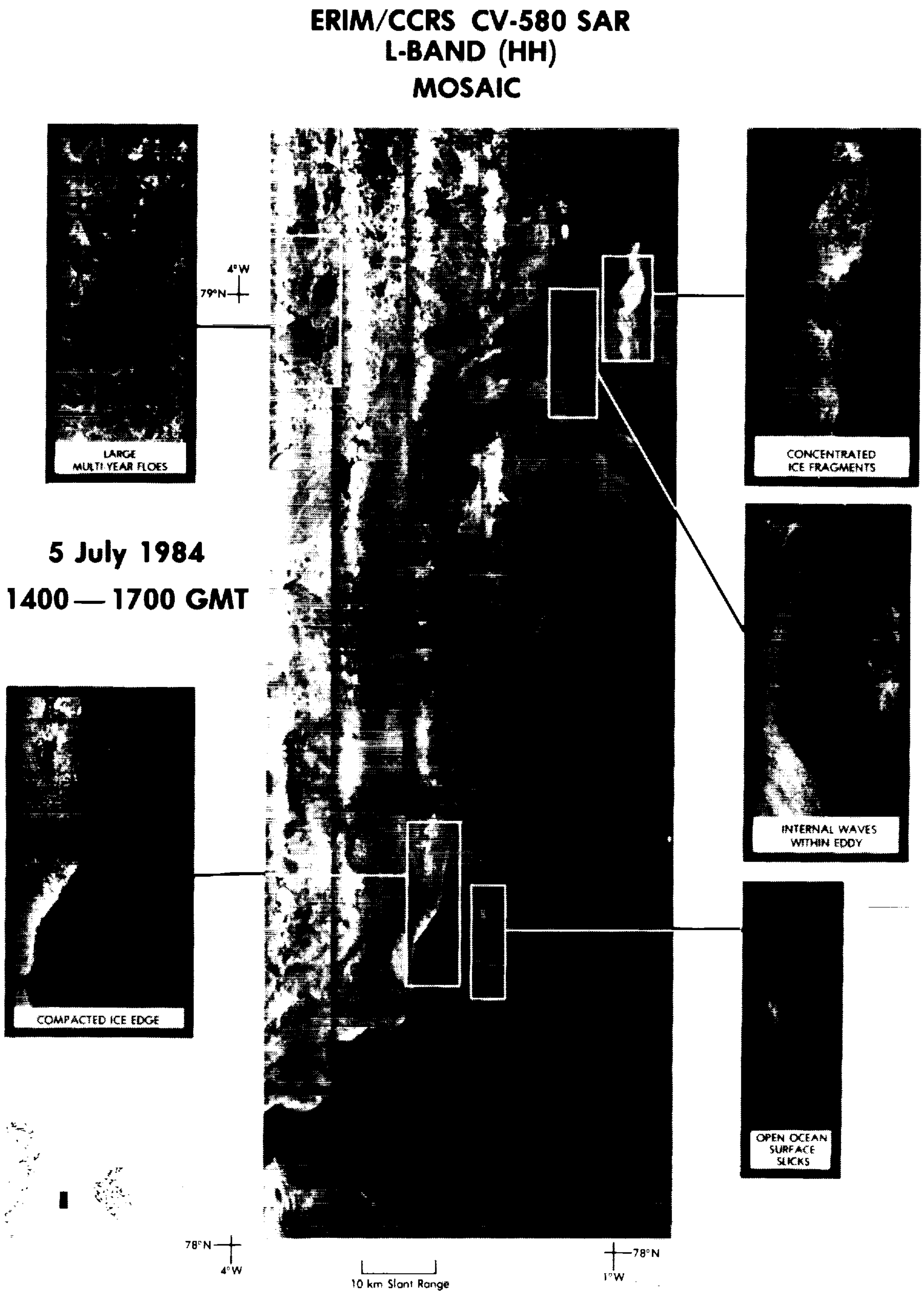

Figure 6A. Aircraft SAR Image of Greenland Sea Ice Margin. (Courtesy R. Shuchman)

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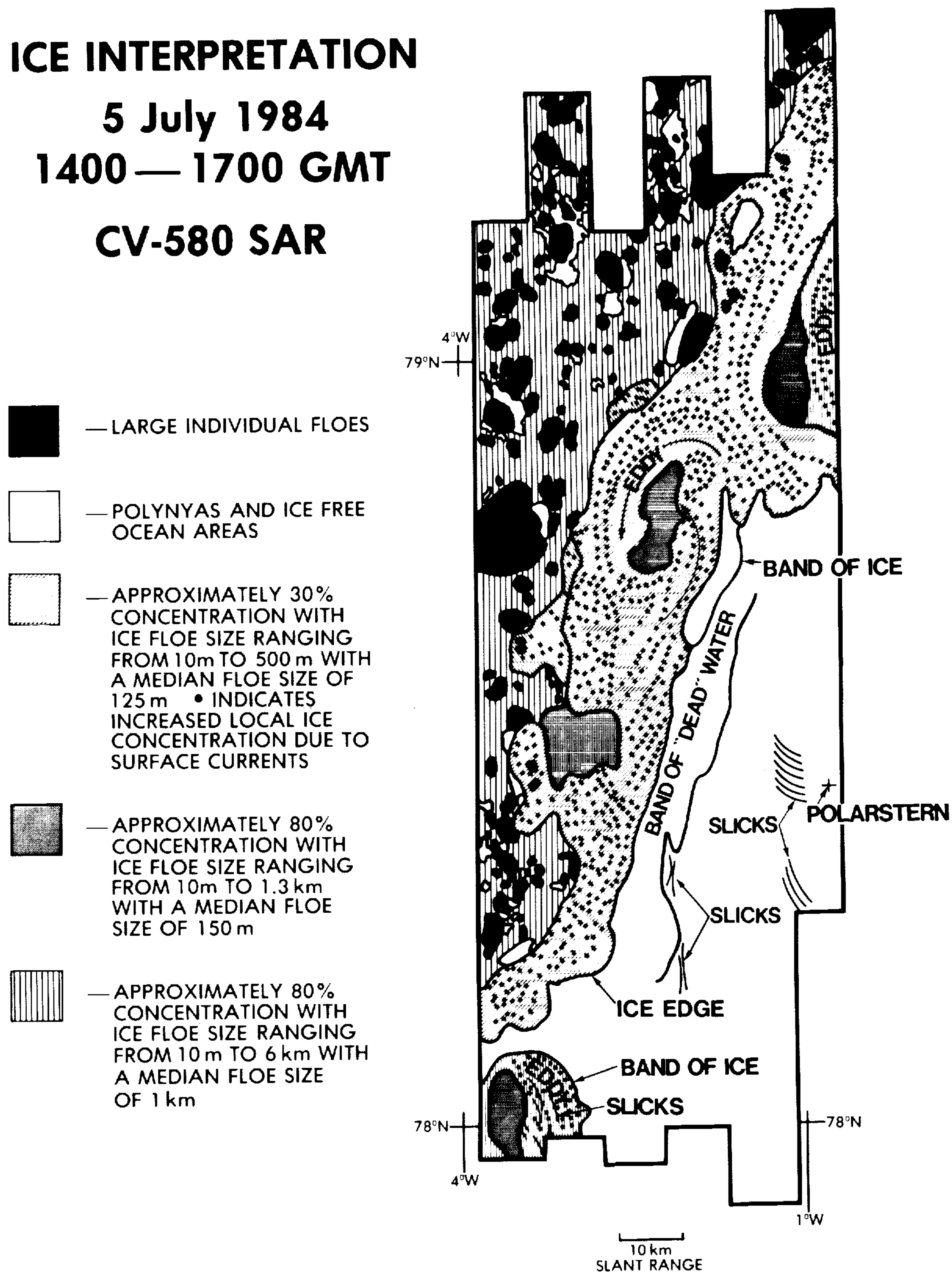


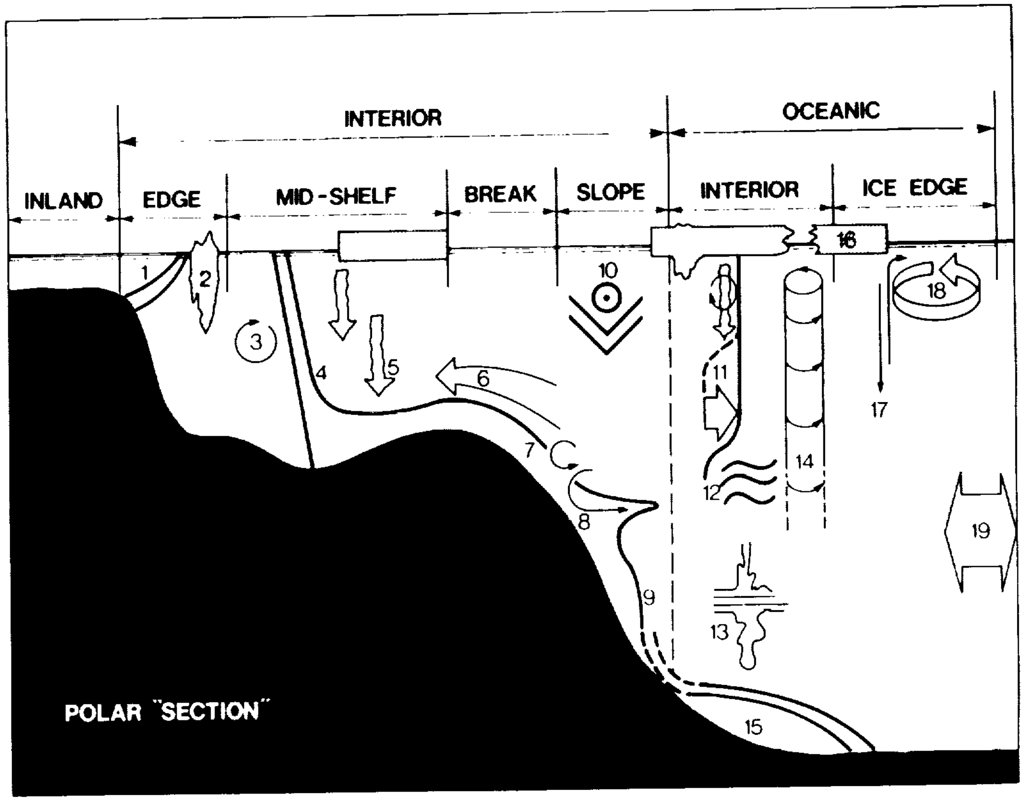
Figure 6B. Ice Interpretation of Figure 6A

5.2 Open Oceans

Numerous oceanographic phenomena are at work in the polar oceans, as shown in Figure 7; many of these, characterized by a wide range of scales, have been detected and studied using radar images including surface and internal waves, current and eddy fields, oceanic fronts, atmospheric conditions, and bathymetric features (Fu and Holt, 1982; Beal et al., 1981). There are a number of important basic and applied oceanographic studies that can be carried out in the seas surrounding Alaska with SAR data. Such studies will provide valuable information, useful also for ocean modeling, on both mesoscale and small-scale variability in circulation as well as on upper ocean dynamics and on the transfer of momentum across the air-sea interface.

Over the ocean, an imaging radar receives backscattered energy principally from short gravity waves; these waves are formed in response to wind stress and are modulated by longer waves and currents. The current-induced modulations are reliably detected under a range of wind speeds from about 2 to 12 m/s but tend to be obliterated by higher winds. Swell and atmospherically-related surface features, such as windrows, are still detectable under higher winds. Understanding the nature of these oceanic features, how the modulations are produced, and the interaction of the ocean surface with the electromagnetic radiation are critical to deriving quantitative information from radar imagery. However, aside from surface waves, theories on imaging mechanisms for detectable open ocean features are just now emerging. Even for the extensively studied surface waves there is no genuine consensus among scientists on detailed mechanisms of imaging, although there is general agreement on basic working theories (Hasselmann et al, 1985). At this point, deriving geophysical information on oceanographic features with an imaging radar requires concurrent, corresponding on-site measurements.

Surface Waves. The Gulf of Alaska and the ice-free areas of the Bering Sea, regions biologically rich as well as important for marine transportation, are frequently subject to intense storms. A SAR can provide directional wave spectra of storm-generated wave fields that will allow one to follow the dispersion and spatial evolution of the waves from their source regions. Such measurements could be of significant value for verifying wave hindcast models and updating forecast models which are particularly important for marine operations. The interaction of surface waves and currents can also be studied by measuring wave refraction, which is dependent on wave properties and current speed and direction. SAR wave measurements can be used in combination with ERS-1 scatterometer-mode data for studying the coupling of wind, waves and currents in the upper ocean. Also, the propagation and refraction of surface waves in the coastal environment constitute useful areas of investigation.



1. RIVER DISCHARGE
2. GLACIAL MELTING
3. COASTAL CIRCULATION
4. SHELF FRONT
5. HALINE CONVECTION
6. SHELF-BREAK UPWELLING
7. SHELF DRAINAGE
8. MID-DEPTH INTRUSION
9. GRAVITY PLUMES
10. SHELF-BREAK JET
11. MIXED-LAYER DYNAMICS
12. HALOCLINE FORMATION BY LATERAL ADVECTION
13. DOUBLE DIFFUSION
14. CHIMNEY
15. THERMOHALINE CIRCULATION
16. ICE-DRIFT
17. ICE-EDGE UPWELLING
18. EDDIES
19. EXCHANGE WITH THE WORLD OCEAN

Figure 7. Simplified Schematic Diagram of Some Physical Processes Associated with Circulation and Mixing in Polar Seas. (Carmack, 1986)

However, there are probable limitations of ERS-1 SAR data for surface wave studies. Based on Seasat SAR analysis, a significant nonlinearity in the measurement of waves traveling in the azimuth or along-track direction may occur due to the random Doppler motion of ocean scatterers during the SAR viewing or integration time (Alpers, 1983; Hasselmann et al, 1985). Depending on the sea state, this nonlinearity may produce overestimation of wavelength as well as a significant shift in measured energy from the azimuth toward the range direction. ERS-1 will be subject to the same degree of nonlinearity as Seasat. This nonlinearity can be reduced practically only by a significantly lower platform orbital altitude such as from the Space Shuttle (Beal et al., 1986; Alpers et al., 1986; Holt and Gonzalez, 1986). The usefulness of ERS-1 SAR data for open ocean surface wave studies under most conditions will generally be confined to narrow-band swell and to broader-band waves either when traveling within about 45 degrees of normal to the satellite direction or when the wind speed is greater than about 16 m/s. Nevertheless the expected lifetime of ERS-1 should add significantly to the knowledge of the wave climatology of Alaskan waters.

Surface waves propagating into sea ice undergo refraction and scattering and can affect the ice cover in several ways through the transfer of energy and momentum to the ice floes which in turn cause ice pack compression, ice motion, and ice breakup due to collisions and flexing of the floes. This in turn can lead to increased melt rates. Waves also affect the formation and dynamics of ice bands and ice edge position. The SAR imaging of swell in ice is shown in Figure 5. As surface waves continue to propagate into sea ice, the higher frequency components are attenuated by friction and stress from the ice itself while the lower frequency waves penetrate into the ice pack for distances which are directly proportional to the decrease in frequency (Wadhams, 1986). This attenuation is dependent on the wave properties and the ice thickness and floe size (Wadhams et al., 1988; Liu and Mollo-Christensen, 1988). From SAR imagery, estimates of the directional wave spectra could be obtained to test theories of wave attenuation, and to examine the effects of wave direction and dispersion. Possibly, estimates could also be obtained of wave height and wavelength on floe characteristics and distribution in the ice margins. Radar-imaging mechanisms of waves in sea ice can also be studied since the reduction of high frequency waves suggests that nonlinearities due to Doppler motion will be reduced and the effects of velocity bunching will be enhanced (Lyzenga et al., 1985; Raney et al, 1989). It should also be noted that the presence of frazil ice significantly reduces short gravity waves in relationship to its thickness and concentration (Martin and Kauffman, 1981).

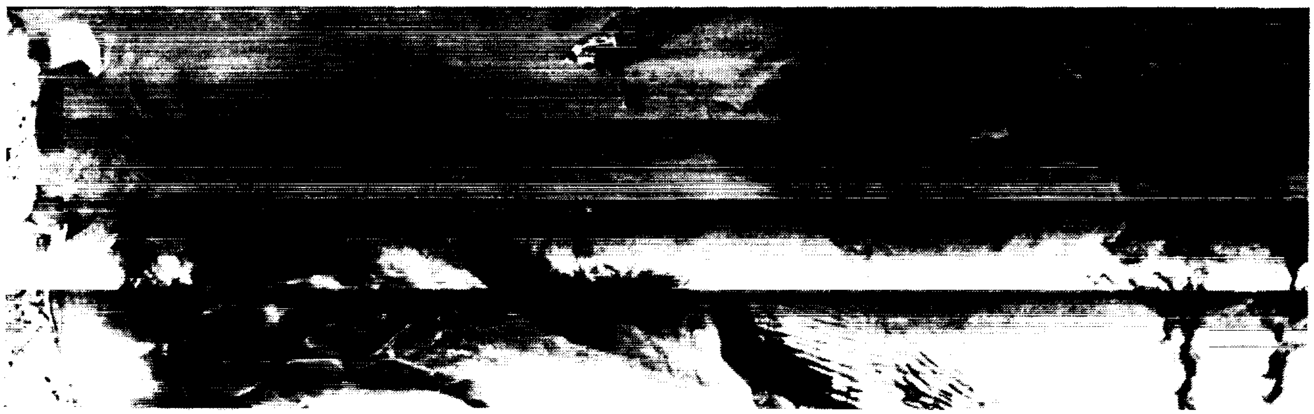
Internal Waves. In the Arctic Ocean, small-scale internal waves are generated under the sea ice due to the motion of pressure ridge keels, buoyancy fluxes, and surface stresses (Morison, 1986). Another type of internal wave which may exist under ice bands, generated by off-ice winds, may act to form and maintain the characteristic spacing and motion of ice bands (Muench et al., 1983). In coastal areas, internal Kelvin waves may occur with some amplification in height, which may affect mixing in the upper layers (Morison, 1986). Given the low tidal energy within the Arctic Basin, these coastal internal waves may occur to any great degree only in summer, when a low salinity lens of surface water is formed from ice melt and river discharge (Melling and Lewis, 1982). Internal waves are also generated during the warm summer months by tidal flow at the sharp seasonal thermocline along the Aleutian Islands and the Gulf of Alaska shelf breaks.

Internal waves are seen by imaging radar as a result of the modulation of short gravity waves by currents. Imaging radars have principally detected tidally generated internal soliton waves over shelf breaks and in shallow water (Fu and Holt, 1984). Waves of this type are shown in Figure 8. From measured group and phase velocities, estimates can be made of the wave amplitude and energetics including dissipation (e. g., Fu and Holt, 1983; Apel and

Gonzalez, 1984). Based on recent studies using SIR-B imagery, it may be possible to estimate the amplitude of internal waves directly from backscatter intensity (Gasparovich et al., 1988). From ERS-1 data, only the tidally generated and larger scale coastal internal waves are likely to be detectable.

Currents, Fronts and Eddies. Mesoscale circulation features, indicating the presence of temperature fronts and eddies and current boundaries, have been observed in the Beaufort, Chukchi and Bering Seas as well as in the Gulf of Alaska (e.g. Paquette and Bourke, 1981; Manley and Hunkins, 1985; Royer and Emery, 1984; Royer et al., 1979; Niebauer et al., 1981). In the ice-covered seas, eddies and fronts have been observed both within the marginal ice zone as well as away from the ice edge, in both winter and summer, with long and short time and length scales, and with sharp temperature as well as haline gradients (D'Asaro, 1988; Johannessen et al., 1987). Fronts and eddies at the ice margins represent a method for the effective transfer of both heat and mass, thereby inducing ice melt, and affecting ice dynamics within the marginal ice zone. For example, in the Chukchi Sea in the summer, warm northward-flowing currents from the Bering Strait are channeled by undersea canyons and affect the ice edge position as well as interactions with pack ice, inducing melt and sharp frontal structures at the ice edge (Paquette and Bourke, 1981). At the edges of the Bering and Alaska continental shelves, eddies have been found to be important for both mixing processes and biological productivity (Alexander and Niebauer, 1981).

While currents, fronts and eddies are perhaps most effectively observed by infrared imaging sensors such as Advanced Very High Resolution Radiometer (AVHRR), data acquisition by these sensors is naturally limited to nearly cloud-free conditions, a rare occurrence in areas near the ice margin (Legeckis, 1978; Royer and Muench, 1977). Imaging radar has proved effective for detecting current boundaries, fronts and eddies. On occasion, the radar can supplant the use of infrared sensors when temperature gradients are quite small. Although the physical mechanisms are poorly understood, imaging radar is able to observe fronts, eddies, currents, and upwelling zones by backscatter variations resulting from changes in the stability of a uniform air flow across a sharp sea surface temperature gradient, the interaction of short waves at current shear boundaries, current motions which produce variable shifts in Doppler frequency, and the characteristic size distribution of ice contained within an eddy at the marginal ice zone. It is also possible to estimate current velocities by measuring wave refraction on SAR imagery. Preliminary analysis of Seasat SAR imagery in the Chukchi Sea indicates that frontal features are detectable in the open sea as well as next to the ice edge, where small-scale eddies are being generated. A study in the Gulf of Alaska indicated that meteorological conditions were such that less than 2% of the available infrared satellite data provided useful information on the seasonal distribution of sea surface temperatures (Royer and Muench, 1977). These observations suggest that there is effective use of SAR imagery in monitoring the mesoscale circulation in Alaskan waters and updating and verifying circulation models.



SEASAT SAR (AUG. 25, 1978)

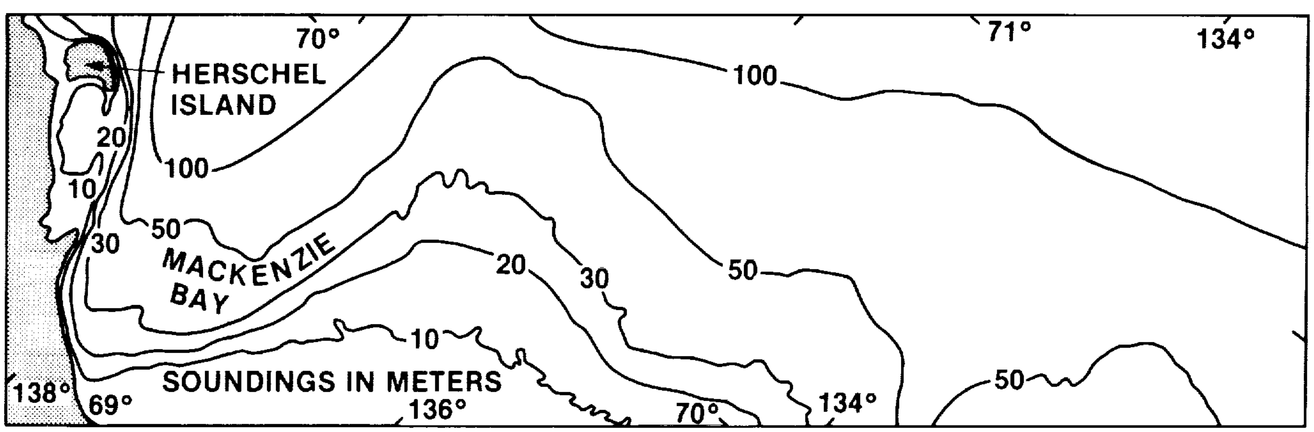


Figure 8. Tidally Generated Internal Waves

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Bottom Topography. The extensive river deltas of Alaska are known to show both seasonal and annual changes in their bottom topography, depending on the discharge levels and sediment load of their associated rivers. The coastal bathymetry of the adjacent seas is also highly variable and can be affected by sea ice scouring. Subsurface bathymetric features have been detected on radar imagery due to the modulation of the short surface gravity waves by surface currents. Internal waves may be generated over deeper bottom features. Wave refraction of ocean swell may also indicate the presence of bottom features. The theory of bathymetric SAR imaging by current modulation has been examined by Alpers and Henning (1984), although the nature of hydrodynamic interactions is not well known. Studies involving estimates of water depth, comparisons of river delta and offshore bathymetry over time, depositional changes, and current estimates would all be both scientifically and operationally useful.

Atmospheric Conditions. As wind-generated short gravity waves are the primary contributors to radar backscatter detected by an imaging radar, atmospheric conditions and features can be discriminated by characteristic variations in the wind fields associated with these conditions. These include atmospheric fronts, intense storms, mesoscale wind variations (generally low wind speeds), windrows (high wind speeds) and the atmospheric stability changes across sharp sea surface temperature gradients. Wind speeds and directions (under certain conditions) obtained from the Seasat SAR compared favorably with scatterometer measurements (Gerling, 1986). Such information on atmospheric conditions is particularly valuable for air-sea interaction studies when combined with data from other ERS-1 sensors. Atmospheric conditions present at the ice edge and in polynyas can be useful for air-sea-ice interaction studies as well.

Marine Activities. Imaging radars are effective in the detection of oil slicks and ships. An oil slick effectively dampens short gravity waves and is therefore detectable on radar imagery. Monitoring of natural and drilling-related oil seepage and oil spills is therefore possible. The major obstacle is separating the oil slick from a low-wind ocean surface and even from frazil ice; a separation may, however, be possible in both the frequency and the image domains. Also, ships and their Kelvin wakes are detectable on radar imagery, providing a possible means for monitoring ship-routing and locating fishing vessels in these waters (Lyden et al., 1988).

5.3 Glaciology

Within the ASF station mask are significant areas of present-day glaciation as well as areas covered by ice during the Pleistocene. These areas are depicted in Figure 9. SAR glaciology is not a well-established discipline as there has been a lack of supporting data, but SAR observations of glaciers are considered likely to contribute to three broad areas of scientific and practical interest. These are the interaction between glaciers and climate, the dynamics of ice flow, and practical applications. Promising research applications can also be examined under the categories of mapping, change detection and surface property examination.

Climate. Glaciers and ice sheets are the products of certain specific climatic conditions, and the changes in these masses, suitably interpreted, are sensitive proxy indicators of climatic change. Glaciers also influence the global system in several ways, the most spectacular of which would be the possible catastrophic breakup of the West Antarctic Ice Sheet leading to significant sea level rise over a period of 200 to 500 years. Within the station mask lies the fourth largest glacier-covered area in the world; this area has been the major contributor to the sea level increase over the last century (NRC, 1985), and is likely to continue to interact strongly with climate changes. Easily observed indicators of glacier health or mass balance include changes in surface velocity, the distribution of surface melt zones, iceberg production rates, and the positions of outer margins. These indicators are all potentially observable by SAR.

Ice Dynamics. The flow of glaciers and ice sheets is a complex process involving three components: internal deformation of the ice itself, accumulation and ablation, and sliding at the base of the glacier. Instabilities in the latter or subtle changes in the calving mechanisms of tidewater glaciers sometimes lead to catastrophic changes in speed and in the position of the ice margin that bear little relation to climate. Dynamical instabilities will need to be understood to sort out the changes due to climate, and these phenomena are also of great interest in their own right. Much can be inferred about glacier dynamics via repeated SAR observations of surface features and changes in the positions of the ice margins that in turn can be used to infer surface velocity; some of these changes may be observable on the time scale of less than a year. It is also suspected that SAR data may be used to bound the accumulation regions on ice sheets and glaciers.

The production of icebergs from calving ice shelves and tidewater glaciers can be evaluated both quantitatively and qualitatively with SAR. SAR observations of iceberg plumes and iceberg density in fiords and lakes permit a first order approximation of the location and intensity of the calving process.

Practical Application. In addition to their effects on sea level, glaciers affect the lives of people who live near them. Their extent and changes have long influenced transportation routes in Alaska. Glaciers also regulate the water supply throughout Alaska. In addition, they are sometimes hazardous, such as when they interact with volcanos or form ice-dammed lakes. Careful monitoring is sometimes required to avoid disasters.

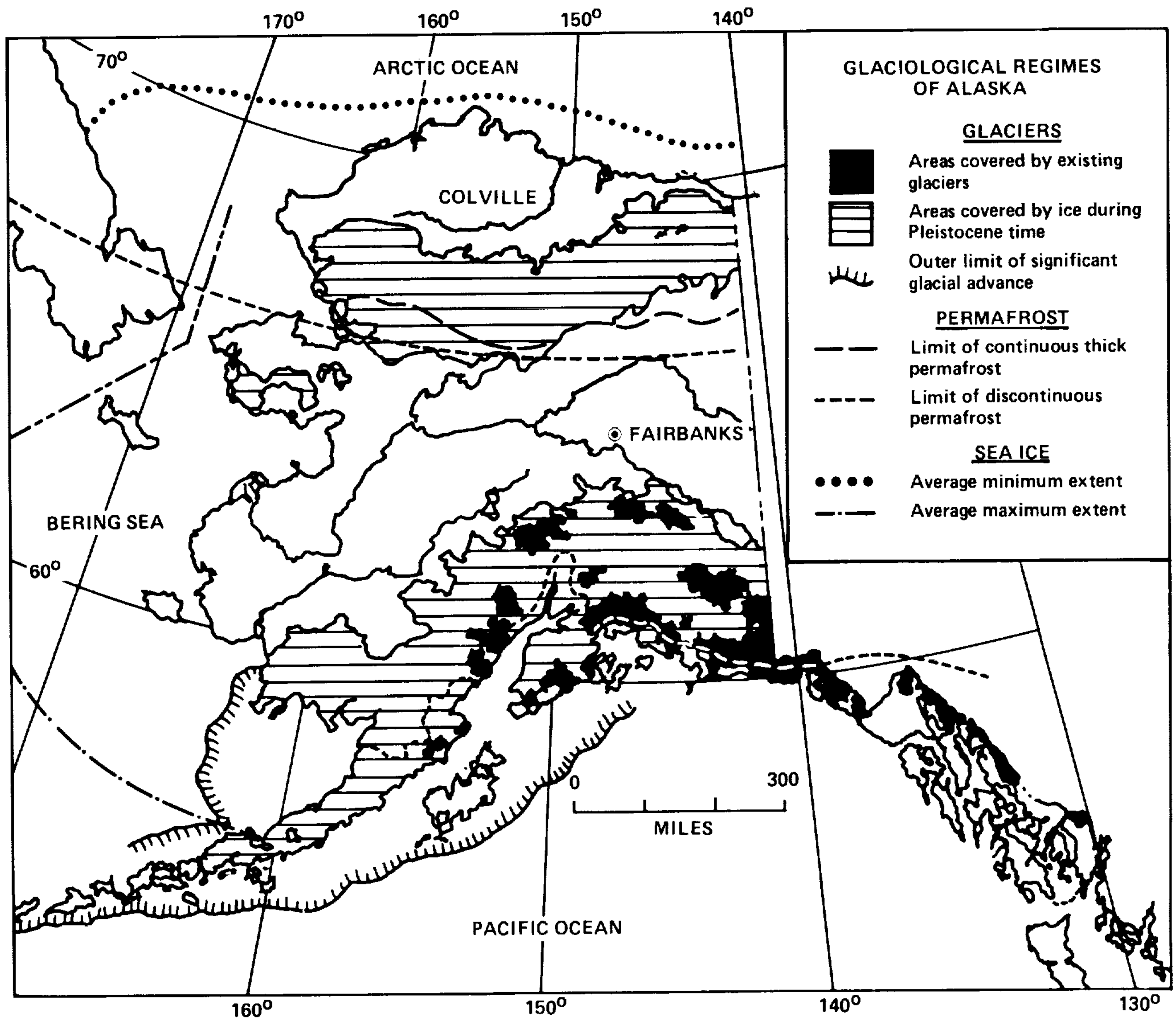


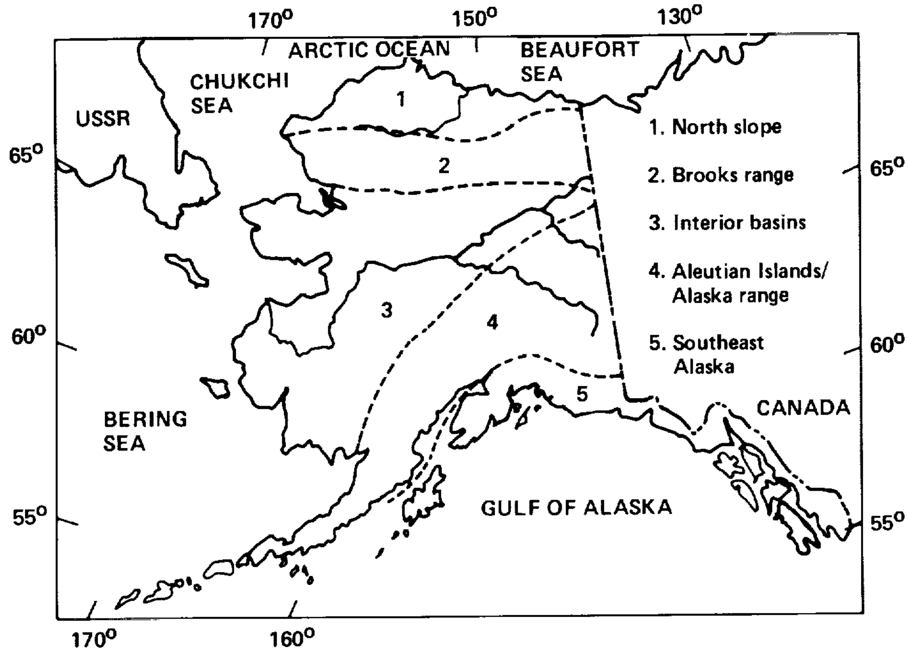
Figure 9. Glaciological Regions of Alaska

TABLE 4: CHARACTERISTICS OF GLACIER FEATURES

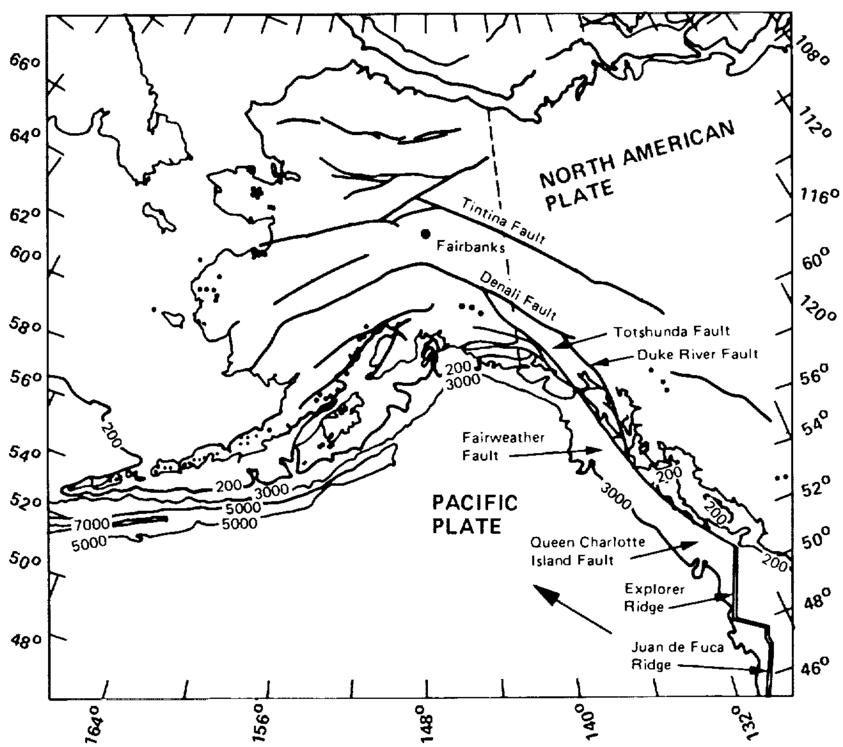
GLACIERS AND ICE SHEETS CHARACTERISTICS		
ASPECT	DESCRIPTION	DIMENSION
SLOPE	0° for ice shelves	100s of km
	5° for mountain glaciers	km
SIZE	Minimum	1 X 5 km
	Maximum	Continental ice sheet
VELOCITY	Mountain glaciers	50-300 m/yr
	Surge	50-100 m/day
	Ice streams	0.5-8 km/yr
FEATURES	Crevasses	15 m wide, ~1 km long
	Moraines	to 100s m wide, 10s km long
	Melt features, streams	1-10 m

There is good comparison between the capabilities of SAR and the scale of glacier features that potentially can be imaged (see Table 4). Hence, several areas for focused research follow from the glaciological objectives (Sec 2.3). Mapping and subsequent monitoring of changing glacier conditions are especially important to establish for the first time a data base suitable for studying glaciers in a global context. Parallel efforts to improve our understanding of the physical mechanisms behind the SAR signal of different glacial regimes and of different surface processes are needed. This will permit accurate interpretation of the results of SAR mapping and monitoring.

Mapping. The use of SAR imagery will be essential in completing the mapping of glaciers and glacial geological features in Alaska. SAR data will also provide a first-time capability for the glaciological community to study changes in glacier systems on a variety of spatial and time scales, ranging from weekly to interannually. This includes data on the past positions of the margins of many Alaskan and Canadian glaciers. Ultimately SAR data will be a significant new component in completing the global inventory of glacier extent and distribution. In Phase 1, the position of the margins of Alaskan and Canadian glaciers can be determined accurately, and numerous older maps, many pre-dating World War II, can be updated. Similarly, glacier surface features such as lakes, medial and lateral moraines, ogives, flow lines, ice streams, ice rises, grounding lines, surficial streams, and crevasses can be identified, inventoried, and mapped. Features such as ogives can be used to produce first-order measurements of rates of ice flow. In perennially cloud-covered remote areas, SAR will make routine glacier feature mapping possible for the first time. Lastly, a variety of ice-marginal proglacial and periglacial features can be identified, inventoried, and mapped with SAR. These features include recessional and end moraines, eskers, outwash plains and streams, and ice-marginal, proglacial, and periglacial lakes. Stagnant-ice-cored moraines, both with and without vegetative covers, can also be mapped.



A. MAJOR GEOGRAPHIC REGIONS OF ALASKA



B. MAJOR TECTONIC FEATURES AND FAULT ZONES OF ALASKA

Figure 10.

Sequential Measurements for Change Detection. Changes in any of the features that can be mapped from SAR imagery can be detected by comparing sequential images if the changes are larger than errors inherent in the data. Examples include:

(a) Motion of distinctive surface features, such as major crevasses and moraines, from which glacier velocity could be deduced.
(b) Advance or retreat of glacier termini and ice-shelf fronts, due to melting, ice motion or iceberg calving. By combining these results on ice shelves with those from (a), iceberg calving rates could be estimated.
(c) Changes in the nature of the ice motion, indicated by changes in crevasse patterns and flow streamlines.
(d) Changes in the dimensions of grounded regions on ice shelves, indicated by changes in crevasse patterns and surface slopes.
(e) Areal extent of seasonal melting, indicated by the reduction in radar backscatter from wet snow.
(f) Changes in the dimensions of lakes associated with glacier damming or rapid drainage.

Surface Properties. The radar wave penetrates dry snow to depths of at least several meters at X-band and several tens of meters at L-band. The returned energy is backscattered from both surface and volume scatterers, suggesting that SAR data might be useful for studying surface and near-surface processes in glaciers. For example analyses of L-band Seasat data and X-band aircraft SAR over the margins of the Greenland ice sheet appear to have confirmed speculation that SAR can discriminate between the rather extreme cases of wet and dry firn. Recent work with radar altimeter data suggests that microwave signatures are affected by important seasonal processes even at the crest of the ice sheet. It is believed that the fundamental geophysical variable affecting the altimeter data is the near surface stratigraphy whose properties vary between winter and summer and with latitude and longitude. These same variations can be expected to modify the intensity of an obliquely incident radar signal possibly providing information on accumulation rate patterns on the ice. Key scientific issues involve the development of a scattering model for inhomogeneous dielectric layers and an improved theoretical and experimental analysis of penetration and scattering in a granular material.

5.4 Geology

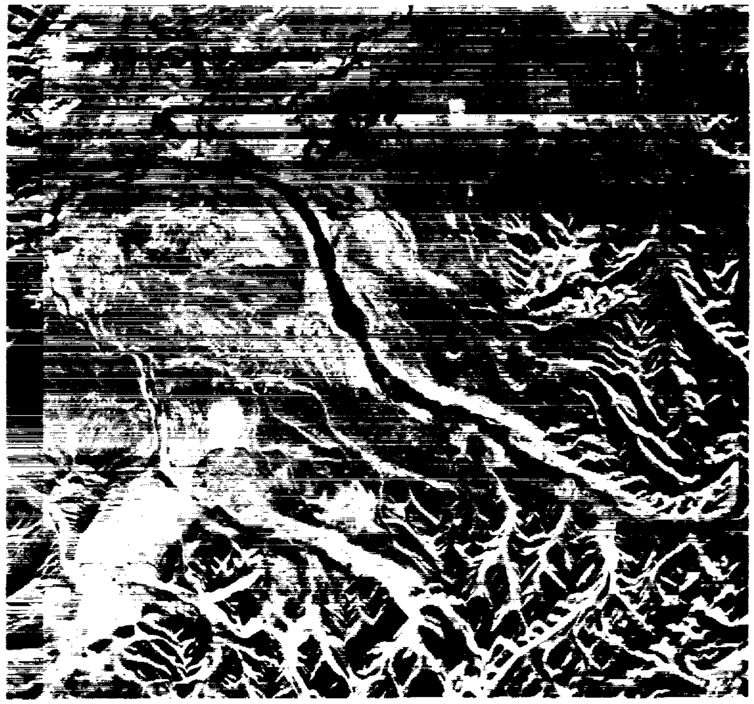
The major physiographic divisions of Alaska (Wahrhaftig, 1965) are broadly grouped into five geographic regions as shown in Figure 10 A. Much of Alaska is composed of allochthonous terranes that are thought to have originated at lower latitudes and to have drifted onto the North American continent by accretionary processes in the Cretaceous (Coney et al., 1980; Jones et al., 1982). Extensive fault zones that bound some of the accreted terranes are shown in Figure 10 B. The tectonically active subduction zone of the north Pacific plate along the south-central coast of Alaska and the Aleutian Islands is particularly noteworthy, with its frequent large earthquakes and more than forty active volcanoes. Potential geologic investigations using data obtained at the ASF are grouped in Section 2.4 under the broad categories of continental evolution and Quaternary geology; specific science opportunities are described in the following sections.

Continental Evolution. Fifty-six accreted terranes have now been described in Alaska in addition to non-accretionary continental rocks and post-amalgamation overlap assemblages (Jones et al., 1984). Some of these terranes may be identified by their morphological characteristics (Morisawa and Hack, 1984). Alaskan remote-sensing data collected at the ASF will permit new analyses of these and other areas.

Structural mapping and interpretation are needed for a better understanding of the tectonic framework of the accretionary terranes and post-amalgamation assemblages in Alaska. Surficial maps at scales of 1:25,000 or larger would provide data to assist in determining the history, rates and mechanisms of regional tectonics from the Cretaceous to the present. Further investigations are necessary to estimate the timing and offsets on strike-slip faults.

Quaternary Geology. The Earth's climate has oscillated between glacial and interglacial conditions several times over the last few million years (Bradley, 1983). These climate variations have resulted in dramatic changes in the landscape including changes in the distribution of glaciers, coastlines, plant communities and aeolian processes. Glaciations during the late Tertiary and Quaternary periods covered about fifty percent of Alaska and profoundly affected the remaining areas that were not glaciated, notably the interior basins and much of the North Slope (Fig. 9). Glacial advances and retreats caused by climatic changes left a geologic record seen in landforms such as glacial moraines, eskers, drumlins, and periglacial features such as permafrost, cryoplanation terraces and solifluction deposits (Embleton and King, 1975; Pewe, 1975; Ford, 1984; Hamilton et al., 1986). Aeolian processes were very active during the glacial maxima resulting in the formation of dune fields and the deposition of extensive loess deposits. Glacial meltwater and floods caused by bursts of ice-dammed lakes strongly affected many major stream valleys (Hamilton and Ashley, 1983).

A.



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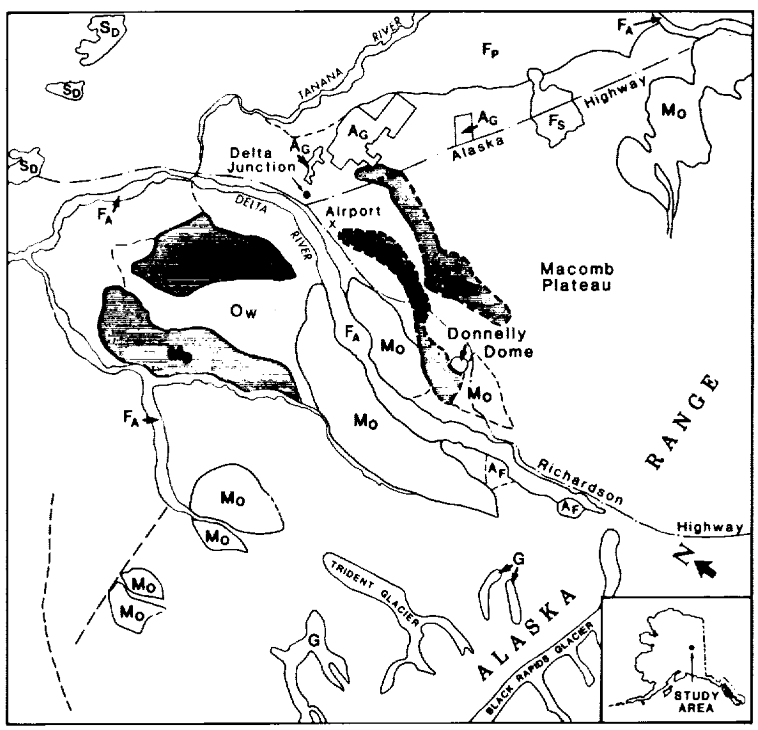


EXPLANATION

M_D-End Moraine, Delta Glaciation
M_O-End Moraine, Donnelly Glaciation
O_W-Glacial/Fluvial Outwash Fan
G -Glacier
F_A-Active Flood Plain
A_F-Alluvial Fan
S_D-Sand Dunes
F_P-Flood Plain
A_G-Cleared Fields
F_S-Fire Scar
—— Suspected Fault

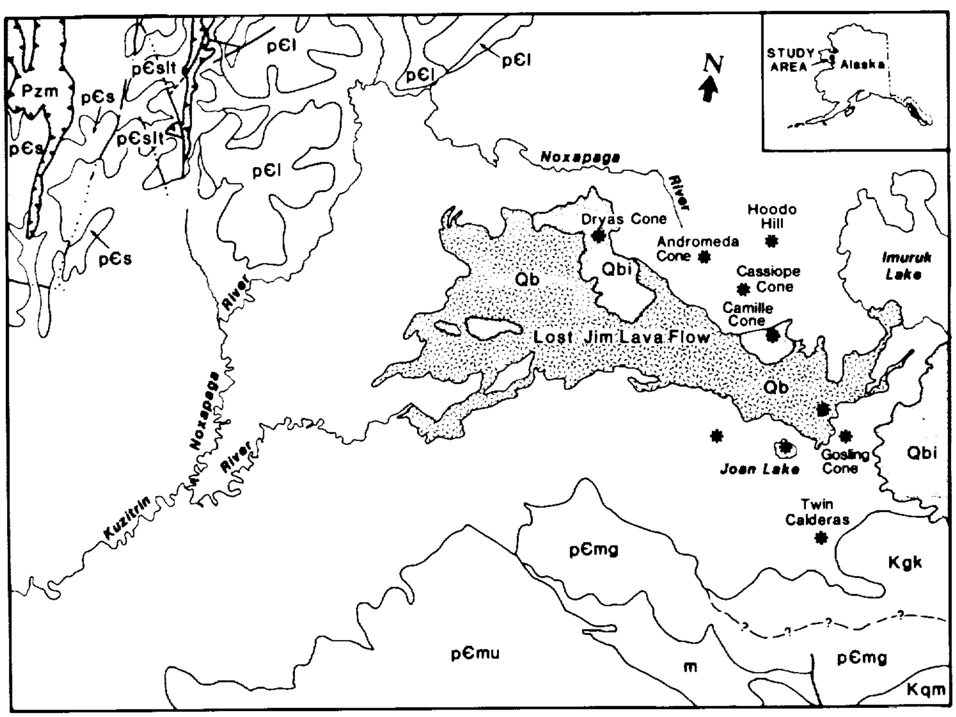
Figure 11. A. Seasat SAR Image Taken on August 4, 1978 of Delta Junction, Alaska Area
B. Geological Map Showing Units Observable on Radar Image

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

A.

B.



EXPLANATION

QUATERNARY
Qb – Dark basalt of Lost Jim Lava Flow
Qbi – Weathered basalt of flows older than Lost Jim Lava Flow

CRETACEOUS
Kqm – Quartz monzonite of the Bendeleben Batholith
Kgk – Biotite granite and quartz monzonite of the Kuzitrin Batholith

ORDOVICIAN
Pzm – Marble

PRECAMBRIAN
pЄs – York Slate
pЄl – Schistose argillaceous and dolomitic limestone
pЄslt – Schistose dark limestone and shale
pЄmu – Undifferentiated metamorphic rocks
pЄmg – Migmatic rocks
m – Marble of unassigned age

✱ – Volcanic cone or vent
Thrust fault; saw teeth on upper plate
High-angle fault

Figure 12. A. Airborne X-Band HH SAR Image of Seward Peninsula Area
B. Geologic Map Showing Units Observable on Radar Image

Refined analysis of this paleoclimatic record is needed to develop a framework for, and to better understand the significance and implications of the (possible) modern climatic warming and its ecological influence (McBeath et al., 1984). Mapping and interpretation of morainal history are needed to identify the former positions of glaciers and determine the limits of glacial cover of different ages on north- and south-facing slopes. Morainal maps may also help in reconstructing glacier profiles and in studying the mechanisms of glacier movement. Figure 11 shows end moraines and other geological features in a Seasat SAR image of the Delta Junction, Alaska region. Figure 12 shows variously weathered lava flows and related structure and rock of the Seward Peninsula area. A SAR image of lava flow in the Mojave Desert is shown on the back cover.

Abandoned river channels and warped terraces or strandlines in coastal regions can provide information concerning the history of tectonic, isostatic and eustatic movements. Multitemporal images can provide data for monitoring rates of coastal retreat and for observing transient phenomena including volcanic eruptions, volcano-glacier interactions (Benson and Follett, 1986), recurring stream icings (Dean, 1984) or the spread of wind-blown deposits from river bars and roads. The distribution and character of periglacial features provide important climatic and environmental information. The distribution of asymmetrical valleys, mass-wasting slopes, cryoplanation terraces, and patterned ground, and their relations to present and past climate are in need of further investigation.

Active Volcanism. Studies of volcanism and tectonic history from the Aleutians through the Peninsula to the Panhandle of southeast Alaska would provide a better understanding of recent and current crustal evolution in this very active zone. This includes active volcanoes which are difficult to monitor as a result of frequent cloud cover and poor illumination in winter. It is important to know eruption frequencies and extents in order to understand the larger problems of terrestrial heat flow and volcano-tectonic interactions, to assess potential volcanic hazards and to provide input to global climate models.

Coastal Erosion and Sediment Transport. Coastal erosion and sediment entrainment and transport by ice are significant areas of study which relate directly to climate, sea level, geohazards and determination of pollutant trajectories. Coastal erosion reflects changes in wave climates resulting from shifting ice regimes, changes in sediment input from rivers to the coastal zone, changes due to ice push of sediments onto the coast from offshore and changes in the coastal and nearshore permafrost regime. SAR data provide opportunities to repeatedly record conditions and study processes during times of extreme stress, e.g., storms, floods and ice events. A major sediment/pollutant transport pathway involves particle scavenging by frazil ice during freeze-up and advection during freeze-up storms. Further advection of sediment may occur after congelation of the ice canopy and during breakup in the spring (see Fig. 4). This mechanism may form the major pathway of sediments from the coast to the Arctic basin. SAR data on coastal frazil ice areas and trajectories of the ice over the shelf during storms and over the winter will be instructive.

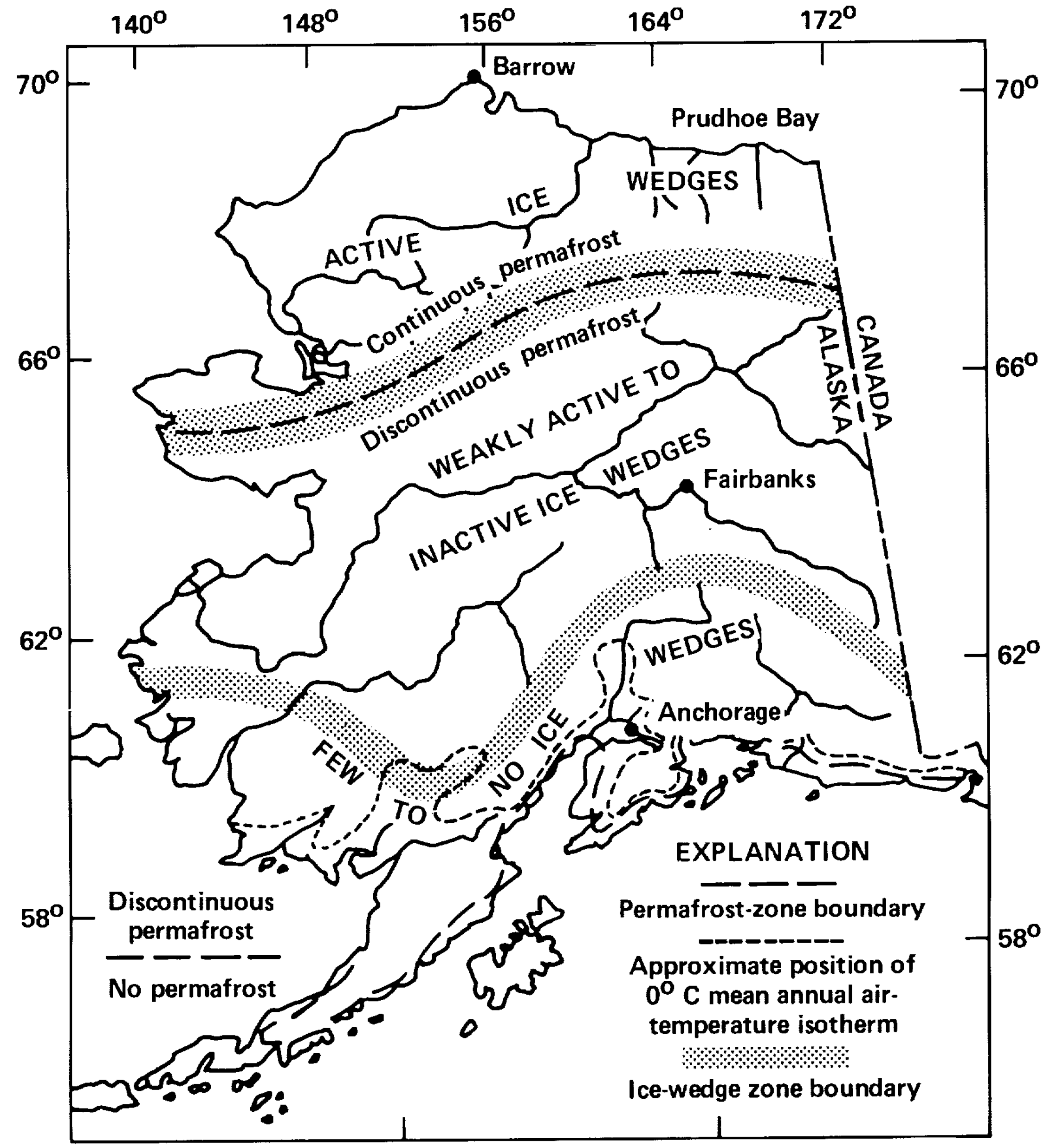
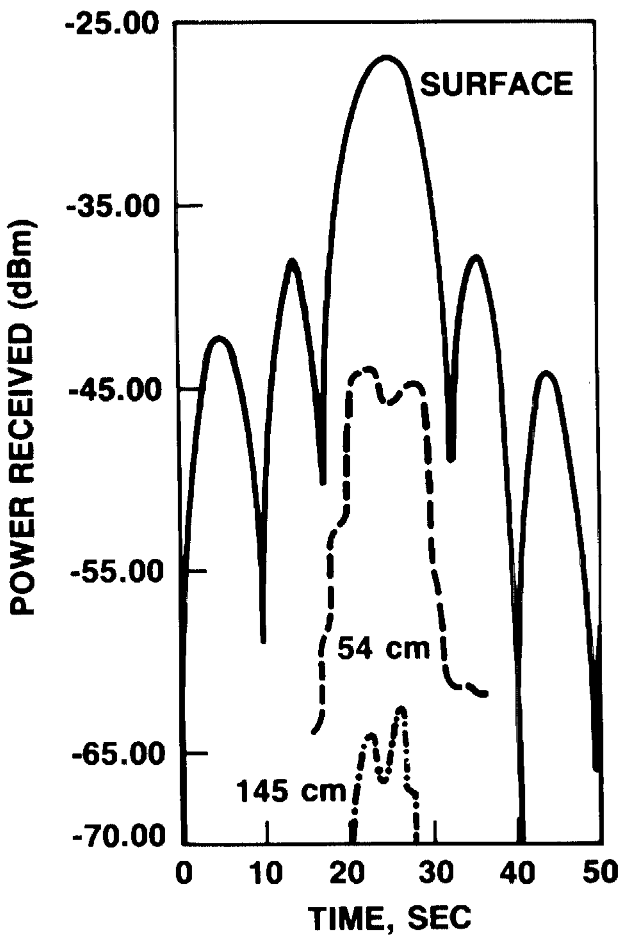


Figure 13. Permafrost Areas of Alaska



RECEIVED POWER AS AIRCRAFT FLEW BY

TRENCH AND SIDE TUNNELS IN PERMAFROST. STRINGS ARE 0.5m APART

Figure 14. Study of L-Band Penetration of Radar into Permafrost, March 1988. (courtesy T. Farr)

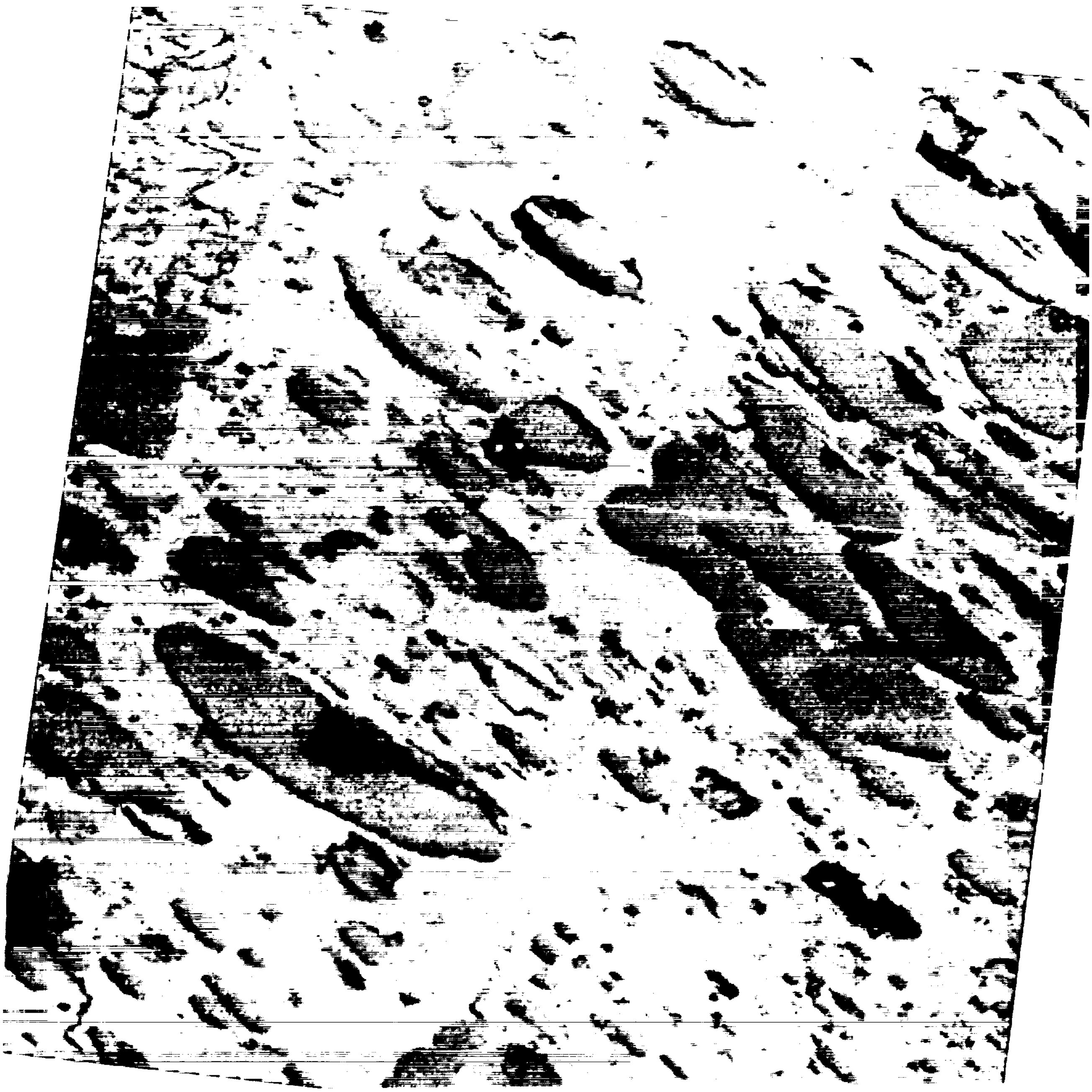


Figure 15. Partially Frozen Lakes as Seen in Seasat SAR, North Slope of Alaska (Hall and Ormsby, 1983)

5.5 Hydrology

Hydrologic science is concerned with the principal fluxes and storages of water in all its states and forms. The principal components to be studied with SAR and optical data from satellites are surface water, soil moisture, evapotranspiration, and snow extent and condition. Excellent opportunities exist in Alaska for the observation and study of all of these phenomena (Hall, 1988).

Soil Moisture and Permafrost. There has been considerable success in monitoring soil moisture conditions with SAR in a temperate environment as evidenced by the SIR-B experiments of Wang, et al., (1986) and Dobson and Ulaby (1986). In the Arctic interest will be the ability of SAR to observe permafrost conditions. Figure 13 shows the extensive permafrost areas of Alaska. Continuous permafrost underlies all of the Arctic Slope of Alaska and discontinuous or sporadic permafrost underlies most of the rest of the state. Permafrost presents unique problems relating to construction, waste disposal, water supply and transportation. It should be possible with the multifrequency SARs that will be available through the ASF facility to detect the difference between frozen and unfrozen surface soil conditions. However, much research is needed to understand and quantify radar's abilities to monitor permafrost. Figure 14 shows instrument placement and preliminary results from a study, conducted in March, 1988, of radar penetration into permafrost (T. Farr, private comm.). For mapping soil moisture, L-band radar is the instrument of choice with C-band radar adding a useful additional sensor in vegetated areas. For bare soils C-band gives information about soil moisture, but integrated over a shallower layer. For measurements through time, accurate multitemporal registration is crucial. Although the differences in backscatter between wet and dry soil are of the same magnitude as those caused by roughness and topography, multitemporal observations should allow these other variables to be factored out.

Evapotranspiration. Evapotranspiration is related to surface wind speed, surface roughness, and the vertical vapor density gradient. SAR data, by providing information on soil moisture, will help in making estimates of regional values of evapotranspiration. Evaporative flux follows a well-defined diurnal pattern in response to the input of solar energy. SAR data on soil moisture at night can help extend estimates to daily integrated values.

Snow Extent and Condition. At both L-band and C-band wavelengths dry snow is nearly transparent. For thick snowpacks in coastal mountains, or for thick snow deposits in river meanders in areas of low relief, C-band radar may provide some indication of snow water equivalence. Because SAR will see through the snow cover, it should be able to monitor soil conditions beneath the snow pack (Hall et al., 1986). It should be possible to distinguish wet snow from dry snow at both frequencies.

At optical wavelengths, snow cover can be monitored during clear-sky conditions. Visible wavelength data distinguish snow from other surface cover and measure the extent to which snow albedo is degraded by wetness or impurities (Colbeck, 1988). Near-infrared data allow an estimate of grain size and the spectral extension of albedo measurements, and short-wave infrared data can distinguish snow from clouds (Wiscombe and Warren, 1980; Warren, 1982; Dozier, 1984). Passive microwave data indicate the presence or absence of snow on a very broad scale and, in general terms, provide some information on its structure (Hall et al., 1986). Experiments with SAR, in combination with other satellite data and surface measurements, are needed to establish the range of usefulness of satellite SAR observations.

Wetlands. Wetlands are environmentally important because they provide anaerobic conditions that allow reducing reactions to occur. Several trace gases, particularly methane, are produced in wetlands. The current information on spatial variability in trace gas production is very poor; measurement of wetland extent and variation would help to understand trace gas evolution. SAR data are useful for measurement of wetland boundaries, even including standing water under trees.

SAR and optical data can provide useful information about the formation of drainage networks over the remote areas that are commonplace in the Alaskan region. Analysis of the extent and pattern of drainage networks can provide an estimate of watershed and basin water yields. This information can be used to assist in the efficient harvesting of water for agricultural and/or industrial consumption or for flood forecasts and river hazard prevention. Also, dual frequency radar sensors offer the possibility of estimating rain-rate profiles from space, a capability that is of great interest in hydrology.

North Slope Lakes and Rivers. Thousands of lakes form from the thawing of ground ice in continuous permafrost. The cause of the orientation is probably related to the influence of prevailing winds on the pattern of thermal erosion (Carson and Hussey, 1962). An example of Seasat SAR imagery of these lakes is given in Figure 15 for the region just south of Dease Inlet (Hall and Ormsby, 1983). In this image, open water is shown in intermediate tones and ice-covered portions of the lakes are the darker regions. It is expected that the open water areas are brighter due to wind-induced surface roughening.

An interesting application of a unique feature of the radar return from these lakes and also from the braided rivers that cross the North Slope becomes possible once an ice cover develops. Typical North Slope lakes are very shallow and develop ice covers that can be in excess of 2-m in thickness. Therefore significant portions of these lakes and rivers freeze completely to the bottom during the late winter and early spring. Fortunately the completely frozen portions of these lakes and rivers can be distinguished through differences in their radar returns (Weeks et al., 1977, 1978). The reason for this contrast is that the dielectric characteristics of ice and frozen soil are essentially the same, resulting in a weak return, while those of ice and water are quite different producing a strong return. This effect can be observed at both X and L-band frequencies and therefore undoubtedly also occurs at C-band frequencies. It offers the possibility of preparing maps of the complete North Slope region showing the exact portions of lakes and rivers where year-round water can be found and where the wintering over of fish is possible (Weeks et al., 1981).

5.6 Ecosystems

Ecosystem process and pattern dynamics include complex interrelationships between biospheric, atmospheric and lithospheric subsystems; scientifically each subsystem must be independently modeled, and the whole must be integrated. Mathematical models of forest succession and soil processes, in conjunction with observations of forest ecosystems, have provided significant insight toward the development of these integrated models and have aided in constructing suitable cause-and-effect relationships. Testing of the models is complicated by time and space scale issues, and it is in this area that remote sensing can make a considerable contribution to ecosystems research (Running, 1984). The flow of water and energy through the environment is fundamental to an understanding of the biogeochemical cycles of elements such as sulfur, phosphorus, carbon and nitrogen. These elements, together with oxygen, water and weather, constitute the principal components controlling ecosystem dynamics. The key concern of biogeochemistry is the interaction of the geological processes which control the flow and transformation of these components in the biosphere. This goal requires knowledge of the rates of biological processes and the capacity and size of chemical reservoirs. This includes determination of primary productivity and gas flux to and from the atmosphere.

The location of the ASF is particularly suitable for studying arctic tundra and boreal forests. The boreal forest is a major ecosystem, containing some 20% of the terrestrial plant carbon (Bolin, 1986); it appears as well to be closely linked to fluctuations in atmospheric carbon dioxide (Tucker et al., 1986). Additionally the northern and southern boundaries of the boreal forest are sensitive to climate change as evidenced by their migrations since the Wisconsin age. A property of the boreal forest that makes it particularly attractive to remote sensing studies is that it is composed of relatively few species, simplifying data analysis. Warming of up to 4°C in the last century has been documented using deep drill-hole temperatures in the permafrost of the arctic tundra. Melting of the permafrost and change in snow cover may result from climatic warming and would lead to changes in tundra productivity, nutrient cycling, decomposition and trace gas evolution.

Biogeochemical cycles and trace gases. Increasing concentrations of CO_2 in the atmosphere are well-documented. The ecological data required to refine estimates of the magnitude and geographic distribution of biospheric carbon dioxide include the geographic distribution of major vegetation and soil zones, the amount of carbon stored in each zone, the state of the vegetation and soils, and the response of the vegetation and soils to disturbance. This information is important for identifying source and sink strengths for CO_2 and other greenhouse gases. The delineation and measurement of vegetation communities and ecotones with ERS-1 data are particularly attractive in the northern latitudes where low sun angles and cloud cover pose observational problems. Human and natural perturbations to northern ecosystems have both produced effects that could result in profound changes in the rates of biogeochemical cycling and trace gas emissions for the extensive arctic tundra, boreal forests and wetlands. The emissions of biogenic and/or anthropogenic compounds CO_2 and CH_4 are very poorly known; nevertheless, these compounds are radiatively active and thus play an important role in global climatic warming. Research should be undertaken to determine the role of land biota and the strengths of sources and sinks of these greenhouse gases within select ecosystems.

C-Band ERS-1 images potentially offer a unique ability to provide information on canopy morphology and structure, canopy moisture status moisture and standing surface water. In vast areas of the tundra, low vegetation density and biomass allow opportunities for determinations of soil properties such as soil moisture and standing water. Although trace gases are not directly detectable with radar data, differentiation of vegetation communities and soil moisture levels may allow prediction of sources and sinks. Change detection techniques using multitemporal ERS-1 data would provide a basis for the study of environmental changes occurring at the land surface including the onset and cessation of biological activity in the soil. Monitoring of snowcover and green-up of vegetation indicates the extent of seasonal gas flux.

For trace gas production, it is necessary to distinguish between conditions of dry and wet soils; these are the conditions which determine whether compounds are oxidized (e.g., CO_2) or reduced (e.g., CH_4). The character and the release rates of many trace gases are intermittent processes often dependent upon the wetness of the soil and the character of the organic matter. ERS-1 data are particularly well-suited for the determination of the extent of standing water and surface saturation, conditions conducive to the anaerobic production of reduced gases.

A major characteristic of northern ecosystems is the widespread occurrence of carbon-rich soils and peatlands. In cold, saturated soils, the rate of production of organic matter exceeds decomposition, resulting in a net accumulation of carbon. Temperature and precipitation are important controls on the rates of carbon accumulation and decomposition; as a result, global climate warming may have a major effect on these processes. Changes in these processes will directly affect trace gas production. That is, any change in carbon storage as a result of climatic warming will probably alter the amounts of CO_2 and CH_4 released to the atmosphere.

Wetlands play a major role in global biogeochemical cycles as sites of very high carbon and nitrogen fixation and gas production. The predominance of wetlands in boreal and tundra ecosystems makes the high latitudes particularly important trace gas source areas. Information derived from ERS-1 concerning the areal extent of wetlands, level of surface saturation, and vegetation (particularly aquatic types) would be useful for predicting trace gas sources and sinks. Time series analysis of ERS-1 radar would allow evaluation of seasonal, interannual, and episodic variability of gas flux processes, while temporal information on inundation patterns and duration and on biomass accumulation and decomposition in wetlands may provide the basis for seasonal and annual estimates of the fluxes of carbon, nutrients, and trace gases to the atmosphere.

Biosphere-atmosphere interactions. Interaction between the atmosphere and biosphere occur at the canopy boundary layer. Information on fluxes of gases, water and energy is particularly important to an understanding of local and regional climate. Of particular concern is the net effect of increased atmospheric CO_2 on vegetation production, the effect of increasing temperatures on vegetation respiration and uptake, and vegetation response to climatically induced ecosystem changes. Information concerning the type of vegetation biomass, canopy moisture content, canopy geometry and surface conditions of soil moisture content, water phase, and understory characteristics are required to gain a full understanding of biosphere-atmosphere interactions. Clearly, measurement capabilities from optical and SAR sensors will be needed. ERS-1 will play a major role due to its sensitivity to canopy moisture, canopy geometry, foliar and woody biomass, and surface boundary conditions.

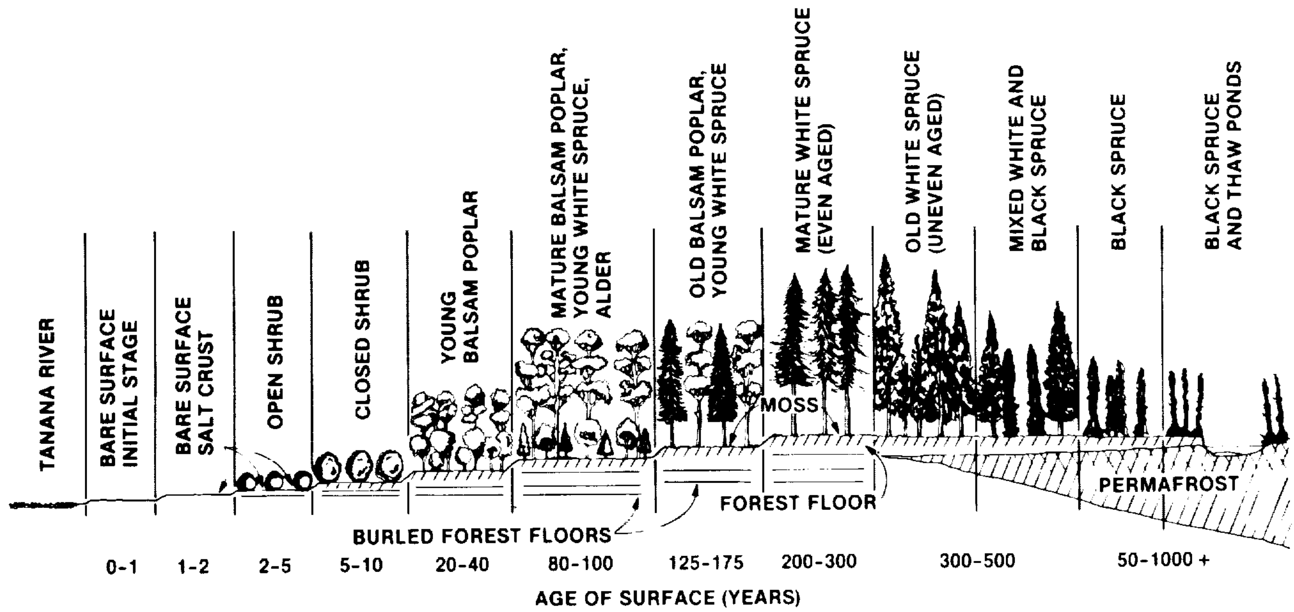
Land Plant Productivity. The physiological activity of plants is a primary driver of energy and nutrient cycles. Thus, monitoring the annual cycle of productivity and its spatial distribution is a key task in the understanding of the working of the biosphere. The ERS-1 C-Band SAR helps with this task in both its spatial and temporal aspects. For example, Cimino, et al. (1989) have demonstrated that the dielectric constant of tree trunks changes tenfold during thaw periods as moisture moves in the trees, and that these effects are visible in P and L-band images (see Figure 16 and Cover.) They may be visible in C-band images as well, thus allowing monitoring of spring thaw over a region using imagery collected on three-day cycles. For some species, C-band may also have potential to monitor phenological change. This is especially applicable to deciduous tree species, since C-band is of a wavelength that interacts with foliage.

The spatial and temporal monitoring of vegetation type and phenologic change is also important to aspects of nutrient cycling and trace gas evolution. For example, bursts of CO_2 released from the trees accompany snow melt at the time of spring thaw. The pattern of thaw in both space and time may thus have important ecological implications, and may be susceptible to monitoring with repeat coverage of C-band SAR.

The annual cycle of land plant productivity has major effects on atmospheric concentration of CO_2. Over the long term, the buildup and breakdown of fixed carbon increases and decreases the size of terrestrial carbon reservoirs. Within the observing radius of ASF are extensive areas of two major biomes - - the conifer forest and tundra biomes. Further, extensive areas of wetlands and peatlands also occur. In the Alaskan panhandle and British Columbian coast, extensive conifer forests of high density and leaf area occur on steeply-sloping terrain. Understanding the global carbon cycle involves understanding the carbon fixation occurring in these biomes and cover types, which is a problem involving monitoring both the physiological state and the spatial distribution patterns of the types. C-band SAR may have application to both of these aspects. Further, both the areal extent and physiological state of these vegetation types will be sensitive to climate change. Thus, monitoring vegetation parameters, for example along a N-S transect, may be of crucial importance as present models of climatic warming due to CO_2 show the greatest effects to be felt in the polar regions.

In Alaska, most forest stands tend to be in a variety of young successional stages (Van Cleve and Viereck, 1981) due to the high fire frequency in upland areas and active erosion and production of silt bars in the river flood plains. Figure 16A (Viereck, 1987) shows the flood plain succession which controls the forest species in the Bonanza Creek Experimental Forest. Primary succession on the floodplain begins with willows and alder followed by balsam polar and white spruce on recently formed river alluvium where permafrost is absent. Slow-growing black spruce and bogs occupy older terraces which are underlain by permafrost. Black spruce, usually associated with permafrost, is the most widespread forest type. Figure 16 B shows the dielectic properties of the black spruce trunks. Shown are L-band data for black spruce during thawed and freezing conditions in March, 1988. The higher thawed-condition dielectric constants would result in a stronger trunk-ground double-bounce signal.

A.



B.

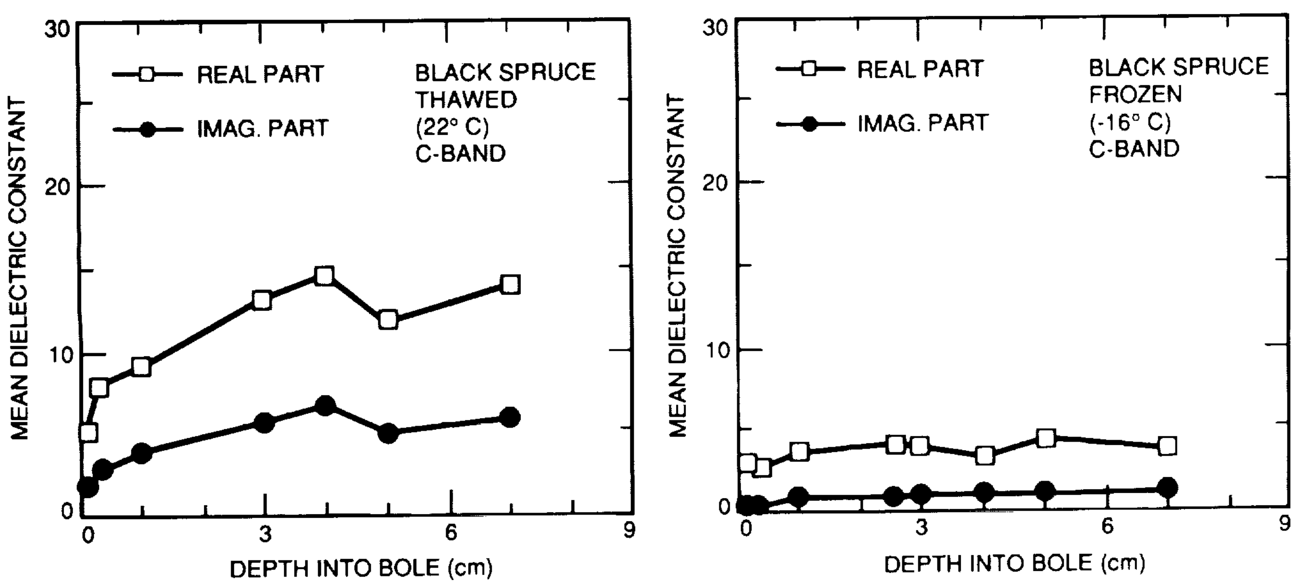


Figure 16. Boreal Forest Succession in Alaska.
A. Successional Stages in Bonanza Creek Experimental Forest (Viereck, 1987).
B. L-Band Dielectric Properties of Black Spruce During Thawed and Freezing Conditions, March, 1988.

Land-Surface Interactions. The northern landscape presents a mosaic of land cover types, in which soils, vegetation, permafrost, and geomorphic processes are mutually adapted. These cover types influence the atmospheric boundary layer by virtue of their surface roughness and evaporation properties, both of which we related to canopy structure. At C-band, the backscatter of vegetation will be influenced by canopy structure, including green leaf area index, leaf orientation, branching geometry, and trunk density. Further, where vegetation density is low, penetration to the soil layer will occur, and soil characteristics (primarily wetness) will also influence the radar return. The problem, however, is that although the signal is sensitive to these factors, it will be difficult to separate the different contributions and obtain canopy or soil descriptions through inversion procedures. Even if such inversion is not possible, it may still be possible to use mapping techniques to establish the areal extent of vegetation types, and from changes in these patterns, infer correlated changes in local and regional climate.

Due to the complexity of vegetative surfaces, quantitative measurements of vegetation parameters will, no doubt, require a multifrequency, multipolarization approach which includes the use of both optical and microwave data. ERS-1 will, however, play a key role in estimating the temporal variability of vegetation as viewed by SAR. Such measurements are useful for monitoring the phenologic state and for monitoring the onset of seasonal environmental events such as freeze-up and thaw. In addition, changing environmental and phenologic conditions may provide a means of isolating the components of the scattering such that a particular biophysical property can be measured.

5.7 Remote Sensing Science

The research activities performed for remote sensing science have provided and will continue to provide the scientific and technical information needed for proper interpretation of remotely acquired optical and microwave data. These activities include sensor design and calibration, field and laboratory measurements, and data analysis and modeling.

Calibration. Absolute and relative calibration of the SAR system by active and passive calibration methods remains one of the major activities to be accomplished. This is a requirement for deriving the surface and/or near-surface geological, hydrological and vegetation information from the SAR image data. Without proper calibration the use of SAR data will at best be limited to qualitative or semiquantitative applications.

Electromagnetic Modeling. Development of models that properly describe the interaction of electromagnetic energy with land surfaces at different frequencies and polarizations remains a high priority. A combination of SAR data and models can provide surface and near-surface information when the models are executed in an inverse mode. This approach overcomes the limitation of empirical methods which are typically site and environment specific. Field and laboratory observations include measurements in different seasons of surface roughness, dielectric constant, microwave penetration and subsurface characteristics. These measurements in turn provide data for modeling activities.

Image Analysis. SAR data analysis techniques have been under development for a number of years and should be actively pursued in the time prior to ERS-1 launch. These include techniques common to other remote sensing data, e.g. stretch, median-value filtering, classification, etc, as well as techniques more specifically applicable to SAR data such as Fourier texture analysis (Stromberg and Farr, 1986), stereo radargrammetry (Kobrick et al., 1986) and polarimetry (Evans et al., 1988).

New Approaches. There are also new and undeveloped or unproven techniques that utilize the unique characteristics of SAR such as its range-Doppler operating principle, use of coherent radiation and complex output. A promising example is interferometry, the coherent comparison of images of the same scene from closely spaced orbits. This method has been shown to be useful for change detection, topographic mapping and velocity measurements of ocean currents.

5.8 Global Change

In recent years the world's attention has focused increasingly on global climate change and its causes and consequences, and studies of these phenomena have become a high national and international priority. The study of global processes and global change is not an independent geoscience discipline; it is, rather, the application of disciplinary data and results in interdisciplinary research. Thus global processes studies pose no additional requirements on data other than that the time and space scales of data taken to satisfy the disciplinary studies be commensurate with the use of the data for interdisciplinary work. Often this means that the time scales must be longer and the space scales larger, an extension that frequently is accomplished with modeling. Figure 17 is a schematic of the general interactions which must be accounted for in the study of global change (Weller et al., 1988)

The Arctic is a critical area in studies of global change. Major interactions between the atmosphere, ice, ocean and biota affect the entire global system through feedbacks, biogeochemical cycles, deep-ocean circulation and changes in ice mass balances. The effects of global climate change in the Arctic can be larger and more pronounced than at mid-latitudes, and therefore these changes can be better observed and monitored. Also, the chronology of past climate changes and their consequences can be studied in the arctic because the signs of these changes can still be seen and analyzed. While the primary variables to be monitored using satellite data are discussed below, other observables are also important for detecting and understanding global change (Barry, 1982; Weller et al., 1988).

A number of significant subsystems of the global climate system can be examined with high sensitivity within the ASF reception area for ERS-1 even though ASF cannot, of course, monitor the complete global climate system. In general the arctic region is involved in subsystems of the global system which are intimately related to surface and tropospheric temperatures, oceanic heat transport, sea level, atmospheric heat, momentum and vapor fluxes, precipitation and insolation.

Glacier Mass Balance. Changes in mass balance of glaciers within the ASF station mask have been responsible for sea level changes in geologically very recent times (NRC, 1985), and these changes may accelerate in the next decades. The technology for the use of SAR data to observe changes in glacier margins, motions and accumulation and ablation rates should therefore be developed. There is considerable active research planned on the glaciers within the ASF mask, and those programs should be encouraged to access SAR data for their work at the earliest time.

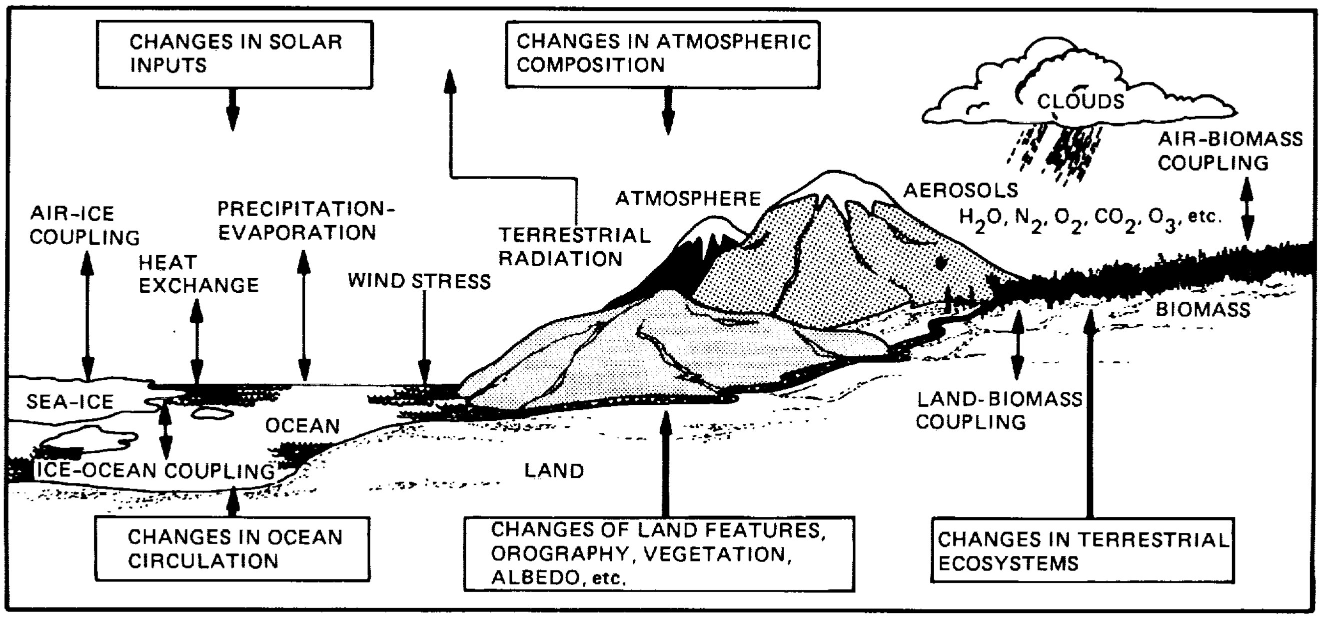


Figure 17. Schematic Drawing of Principal Components and Interactions in the Global Climate System

Sea Ice Conditions. The extent and thickness of sea ice is a consequence of dynamic and thermodynamic processes at work in the air-ice-ocean system. This system is susceptible to changes controlled by extra-arctic processes such as the fluxes of heat momentum and vapor into the arctic, the strength of storms and the temperature of the upper layers of the sea. Models have predicted how global climate change will influence the ice and how the ice cover will in turn influence the air and water circulation and the global climate through feedback processes. It is the task of ASF scientists to relate the observations of sea ice to the forcing elements of the climate system. This task will require that air temperatures and winds, sea surface temperatures, snowcover, cloudcover and other variables be monitored.

Snowcover. Snowcover is a similarly active player in the global climate system; its extent is controlled by precipitation and air temperatures, and in turn it strongly influences the total insolation both through its high albedo and through the role of the melt water. The use of SAR to study snowcover is a developing technology, but its overall potential is established and should be pursued in the context of understanding the role of snowcover in the global radiation and hydrological budgets.

Permafrost. The use of SAR images in the observation of permafrost and permafrost terrain and features is also a developing technology; there are no tested data interpretations. However, existing data suggest that frozen ground produces microwave property changes that are resolvable and that changes in permafrost vegetation and geomorphic features are also identifiable. Since the margin of the frozen ground is the direct consequence of the mean surface temperature, the role of permafrost mapping in the monitoring of global climate is obvious. This area should receive immediate attention from the scientific community.

5.9 Applications Demonstration

Applications demonstration projects will initially be directed primarily toward demonstrating the potential of SAR data for improving the efficiency and/or reducing the costs of operational or management tasks which are currently underway. However, the program will be responsive to new applications which become feasible because of the unique capabilities of satellite-based SAR systems to acquire data regardless of cloud cover or lighting conditions. In addition, as the science program evolves and new data enhancement and interpretation techniques become available, it is certain that additional applications opportunities will develop. Similarly, questions arising from ADP projects can be anticipated to suggest new directions for the science program.

The possibilities for applications demonstration research using data collected by the ASF range across all of the disciplines discussed above and will be described more completely in a separate report. Only a brief description is given here.

Immediate Applications. There are opportunities for immediate applications in which it seems clear that the satellite-based SAR data will contain the information necessary for an application without the need for new data enhancement techniques or extensive ground truth studies. Subject areas in this category include, for example, marine transportation in ice-covered waters, land-use mapping, and monitoring the termini and calving rates of tidewater glaciers. The range of opportunities can be expanded by including topics for which research (mainly in the form of comparisons with on-site data) is required to verify that the data needed for a particular application can be extracted from the SAR data. Examples of applications of this type might include the discrimination of water masses to support commercial fishing operations, tests of the use of SAR data in wave spectra applications, and monitoring ice jams in rivers for evaluation of flood potential.

Potential Applications. The possibilities for applications demonstration projects become even broader if potential applications are included in which (1) research is required to establish the connection between a physical process and the SAR data, or (2) the synoptic, repetitive, all-weather capability of SAR is used as the basis for establishing programs to monitor and manage resources over large areas (e.g., an entire river basin). Projects such as these might require new data processing and enhancement procedures and/or additional basic science in order to establish the application. In these cases, the effort could be coordinated through the appropriate science program.

6. SAR DATA PRODUCTS NEEDED IN SCIENTIFIC INVESTIGATIONS

It is clear from the preceding discussions that the SAR images to be produced at ASF contain information of significant and particular value to geophysical studies in Alaska and its adjoining waters. This information is contained in the SAR image data, but is not the SAR image *per se*. In general it is necessary to extract the information from the SAR image by image analysis. In some cases the application of image analysis techniques is intensive and non-routine involving up to hundreds of hours of expert investigator time per image. In other cases the analysis is far simpler involving minimal operator supervision and the utilization of automated procedures. In what follows the data products required are examined for each discipline and recommendations are formulated addressing the issue of where and how this information should be generated.

6.1 Sea Ice and Polar Oceans

The oceanic processes of greatest significance in the waters around Alaska are those related to the presence of ice and include its thickness, compactness and type, its motion, the presence and energetics of ice-margin phenomena such as bands and eddies, and the penetration of oceanic swell into the ice pack. Thus the data products required from the SAR images are ice concentration, ice type, ice motion, directional wave spectra, and ice margin structure. The first three variables can be developed from SAR images using known techniques. Directional wave spectra may be derivable with sufficient accuracy, but at present the imaging mechanisms for variations in SAR return resulting from waves passing through ice fields are not established, nor has the effect of swell in the alteration of ice pack properties such as the floe size distribution been fully explored. Thus, the study of waves in ice by SAR is still in an early research phase. Likewise, the observational technologies for bands and eddies at the ice edge are not well-known although these features are believed to be significant in affecting the dynamics and thermodynamics of the marginal ice zone.

Other data products will undoubtedly be identified as being significant to the description of the ice pack, and these may well turn out to be observable from SAR. For example, the SAR images from Seasat often showed frazil ice in "tadpole" streamers presumably organized by Langmuir circulations. At present the exact oceanographic significance of these features is speculative, and their observation requirement cannot be precisely stated. Other examples of possibly significant observations of ice pack properties in SAR images are the orientation and frequency of occurrence of leads and ridges, the geometry of open-water areas, the change of backscatter level with time through a season, and the estimation via SAR data of the sediment content of the ice from coastal regions. To better understand and formalize the study of these phenomena, sequential SAR images should be acquired and examined in detail by investigators interested in ice processes; no higher level data products are required.

6.2 Open Ocean

There are many useful data products for open ocean research in Alaskan waters. While surface waves are the features most widely studied with SAR, the expected nonlinearities for azimuth-traveling broadband waves restrict the conditions of usefulness of ERS-1 data for wave studies.

Useful products from SAR for ocean circulation and mesoscale features include the location of current boundaries, mesoscale eddies and temperature fronts. Current speed may also be derivable from wave refraction measurements provided that the surface waves are linearly mapped. For internal waves, useful products would be the location, wavelength, length of wave crest, orientation and number of waves in each wave packet, and the intensity of each wave. Aside from the intensity of internal waves, all the products for circulation features and internal waves are directly measurable from the SAR imagery and should be derivable automatically by incorporating existing image analysis techniques, e.g., edge detection. To have the image intensity of internal waves to be meaningful in determining wave amplitude requires radiometric calibration and accurate modeling of the effects of internal waves on oceanic surface hydrodynamics and radar signatures. For surface waves, wave direction and wavelength are important data products which are derivable through two-dimensional Fourier analysis. However, the accuracy of these measurements is directly dependent on the understanding of the various imaging mechanisms and the characteristics of the waves themselves with respect to the satellite velocity direction. Considerable research is required in order to derive the very important parameter of wave height from SAR imagery. Obtaining fine-scale measurements of wind speeds, both within and outside the ice cover, and even wind direction (with a 180° ambiguity) from the orientation of windrows is desirable but again requires system calibration and an accurate algorithm for the SAR wind speed transfer function.

6.3. Glaciology

There are numerous data products for glaciological studies that principally involve mapping and monitoring of features and glacial dynamics derived from sequential imagery. Products that can be derived by accurate mapping include the areal boundary of glaciers and ice sheets, the location of many surface features including crevasses, flow lines, moraines, ice streams, and ice rises, as well as the detection, size, density, and rate of production of icebergs. Data products derived from sequential imaging include ice motion as obtained from feature tracking and changes in features, changes in the distribution of wet and dry snow, and changes in the position of glacier termini and ice shelf fronts. Products focused on property changes will add to the global inventory of the extent of ice sheets and glaciers as well as glacier distribution, and can be used for monitoring the mass balance of glaciers as a function of climate change and for the study of the consequences of those changes.

There are two requirements related to change detection technologies:

1. The analysis technology for generating sea ice information from SAR data should be utilized, on a trial basis, for glacier analysis. Many of the generic features observed on glaciers are similar in geometry to those of sea ice, e.g. crevasses to ridges or leads; thus, there is reason to believe that the sea ice classification and motion algorithms may be applicable to the glacier case. If the results are promising, modifications to these software packages should be evaluated and, if appropriate, performed.

2. The technology to overlay SAR and optical data should be installed at ASF as a routine capability. Recent work has shown that overlaying of optical and SAR images can be used to discriminate between signal-intensity variations caused by topography and those caused by grain size. Also the overlay technique will be crucial for quantifying changes in the position or structure of the glacier.

6.4. Geology

Data products that will be generated from SAR image data for geological studies include maps of geologic structural features, lithologic units, surface morphology, coastal changes, volcano distributions and morphology, and surficial processes. These maps will provide information on coastal erosion and accretion as well as on the tectonic and volcanic history of Alaska, including the characteristics of active volcanoes. Also of interest from these maps will be examination of glaciation during the Quaternary period by mapping glacial moraine advance and retreat and drainage patterns resulting from glacial melt and crust movement.

Other potential products include surface roughness maps, but these would be limited by the extensive forest cover in Alaska. In areas of complete forest cover, maps of image texture (Stromberg and Farr, 1986) can also be used to aid in lithologic discrimination. Such products can be enhanced by using multiple data sources, especially optical sensors. These multiple data sets require the development and ready availability of accurate registration, geocoding, and terrain correction algorithms. Of particular interest to geologists is the ability to generate large scale mosaics covering entire physiography regimes.

6.5. Hydrology

For hydrology studies, the data products from SAR involve the flux and storage of water in the Alaska region. One product will be soil moisture content which includes mapping the unfrozen and frozen surface condition of permafrost as well as the areas of wet and dry soil and the diurnal evapotranspiration flux. Maps of soil moisture can be made from both L-band and C-band data. Another product will be maps of snow extent, snow water equivalence, and state (dry versus wet). These products are best made using an optical sensor with some additional information provided by C-band SAR. Other data products include maps of the areal extent of wetlands (standing water), terrain characteristics such as drainage patterns, and frozen and unfrozen lakes and rivers on the North Slope. These data products can be measured from both radar systems but considerable research is necessary to provide accurate scattering models that consider temporal and spatial variabilities.

6.6. Ecosystems

The principal data products for ecosystem studies will address both canopy characteristics and soil moisture, and include maps of the canopy geometry, extent, and above-ground biomass using both SAR data alone and SAR data combined with data from optical sensors. Land cover type maps may also be produced as appropriate for monitoring environmental change and modeling regional matter and energy budgets. Research is still required to model the radar scattering properties of the various Alaska vegetation types; these models will be dependent on the basic canopy structure, moisture, season, and diurnal variations. Data products will also include temporal hydrologic and vegetative information for high latitude wetlands.

6.7 Remote Sensing Science

Remote sensing science data products are not unique; they are the products required to support the discipline areas specifically discussed.

6.8 Applications Demonstrations

Data products for applications demonstration projects will generally be similar to those of the scientific disciplines. However, applications involving sea ice and open ocean applications and those for monitoring natural or man-made environmental disasters will require the analysis of data and the production of data products within a matter of hours after acquisition due to the time scales of change of conditions for these events. Rapid data analysis will be possible within the ASF facility through the quick-look capability of the SPS, and the use of this capability will accommodate the needs of some users. However, others will require the data to be transmitted in real-time to other facilities for analysis, product generation and possible retransmission to field sites or other user facilities. The equipment required for this data transfer will not be part of the ASF, but ASF should provide interface for such systems (e.g. the SAR Communications System or SARCOM, which is being developed by NOAA), and ASF should seek to facilitate the access to the ASF data by the general user community.

7. GENERATION OF DATA PRODUCTS FOR ASF STUDIES

7.1 SAR Products

Data products required to support the ASF Science Program all utilize the SAR images output of the SAR Processing System. For some disciplines these data sets are further processed. In general, oceanographic analyses require direct evaluation of a geophysical variable, e.g., a wavelength or an ice type, from the SAR image. The resulting quantity has geophysical rather than radiometric or arbitrary units. Typically, the terrestrial sciences require further intensive processing of the SAR images prior to the evaluation of geophysical variables. Processing capabilities required for terrestrial sciences include:

• SAR Terrain Correction. The correction of the SAR image for the error introduced by the inability of the SAR processor to distinguish between height differences and range differences in targets.

• Precision Location. The identification, in either absolute earth location or relative location with respect to another image, of the location of a SAR pixel to about one-quarter of a pixel.

• Coregistration. Mapping to common pixel locations of multisensor and multitemporal data at location accuracy finer than one pixel.

• Reregistration. The remapping of some data sets into other projections in order to obtain accurate coregistration.

• Geocoding. The location of SAR pixels on an earth-fixed grid, preferably a grid whose exact grid spacing and locations are agreed to internationally.

• Mosaicking. The capability to mosaick multiple SAR images with an accuracy finer than one pixel.

• Change Analysis. The capability to generate an image that is the difference of two input images covering common elements of the surface. This product will utilize as input the output of the geocoding processor.

• Stereo Analysis. The capability to analyze two images covering common surface area collected at different azimuth for topography and anisotropy. (Cannot be done with terrain-corrected images.)

• Geophysical Processing. Reduction to such biogeophysical variables as above-ground biomass, surface roughness and dielectric constant.

7.2 Geophysical Products to be Generated At ASF

The PSWT strongly maintains that a number of situations call for the generation of geophysical products at UAF through implementation of a Geophysical Processing System (GPS). Therefore, the PSWT recommends that a GPS be established at ASF to provide such products as appropriate. Situations that call for the production of geophysical data at ASF are those for which the production technology is mature, for which there are a number of users for a given set of geophysical products and for which there is a clear benefit in centralized processing, e.g., in the assurance of data consistency.

Although ASF SAR images will contain information of great value in the study of oceanic processes in ice-covered and open seas, these images need further processing to develop the geophysical products that are required. The generation of these variables is clearly appropriate for central processing at ASF. Thus, the Ice and Oceans Panel recommends that a GPS for ice and ocean variables be implemented. In the past NASA appointed committees such as the Ice Motion Algorithm Group and the ASF Science Review Group have pointed out that:

1) Algorithms are in sufficient readiness to produce the information most needed; the ice motion, concentration and type and the long-period swell orientation and wavelength. These variables can be derived from ASF SAR data in a routine fashion in which there is little or no expert-operator supervision in the data processing. The capability for such processing should be in place in time for the launch of ERS-1.

2) Performing the processing at ASF is optimal from the standpoint of product consistency, timeliness, and overall efficiency. It is also important that the data are generated at a facility which can also do a suitable job of archiving and distributing the results.

3) As the computer and operational resources to support a useful number of products are modest, this first effort at the routine generation of SAR-derived geophysical products can be approached without resorting to massive computer systems with their attendant risks and costs.

4) An ice-ocean Geophysical Processing System or GPS should be implemented at ASF to routinely generate the key variables of ice motion, concentration and type and oceanic swell.

As planning for ASF matures, other disciplines may wish to specify and propose implementation of specialized GPS capability. Products under discussion at this time include maps of forest cover, surface water coverage and snow and snow-melt mapping as well as an expanded set of open ocean products.

7.3 Geophysical Image Analysis at ASF

In addition to the routine processing of ASF image data to geophysical variables, there is also a clear need for the implementation at ASF of an investigator-operated image analysis system for intensive manipulation and examination of SAR images. This system should be used by SWT members who reside on a temporary or permanent basis at UAF, SWT members who are visiting UAF, e.g., en route to and from field campaigns, ASF staff members utilizing image analysis in quality control, and when possible without interference, other UAF scientists.

7.4 Geophysical Analysis and Processing to be Done At PI Institutions

Although the above PSWT recommendations are designed to both minimize and standardize the image processing done by individual investigators, there still remains a requirement for a significant amount of this type of analysis as many of the possible applications of SAR data are in the exploratory and developmental phases. The PSWT recommends that the status of image processing capability be closely examined, and that remedial action be taken if it is not commensurate with the data flow and scientific opportunity of the ASF.

In particular, the PSWT further recommends that the image analysis capability at UAF be extensively upgraded. There are a number of reasons for this action. First, UAF will inevitably become the center of action for the satellite analysis work done with ASF data because of its central location in the geographical region being studied and because of the ongoing data processing activity there. Thus the SWT members can expect to find themselves working there on a regular basis and will need good image analysis support. Second, UAF staff will become intensive users of ASF data and will soon constitute the "corporate memory" of the science and operations of the facility. It is in the best interests of the scientific community for these staff members to have access to adequate image data analysis tools. Third, there is a clear need to establish a quality assessment activity in conjunction with the ASF as a whole. This program will need to have current-technology image analysis equipment to do its job.

8. PRELAUNCH RESEARCH REQUIRED FOR ASF SCIENCE PROGRAM

In the discussions above, the PSWT has reviewed the science objectives for the disciplines to benefit from ASF data and has made a number of recommendations relating to the data, data products and geophysical quantities required. The status of algorithms for generating the data and geophysical products has been reviewed. There are also specific research and development tasks and data acquisitions which must be performed to supply key information on image interpretation or to further the effectiveness of the recommended processing. These are examined below.

8.1 PSWT Panels

Much of the work that needs to be done in the scientific community in preparation for ASF will continue to be collectively reviewed and performed by panels of the PSWT. At this time, Ice and Oceans, Land, Glaciology, and AOS panels have been formed. In addition to their advisory capacity, the panels are also charged with insuring the exchange of ideas and techniques among established investigators in each of the disciplines. In particular, the panels will determine the objectives, effectiveness and status of standard algorithms for the generation of required geophysical products.

A specific working group to be continued as a PSWT Panel is the Ice Motion Algorithm Group (IMAG), which has met twice to formulate the algorithms for the ice GPS at ASF. This panel will continue to examine the technology and results of ice-motion detection schemes using SAR data. The Ice and Oceans Panel will also analyze the capabilities of existing algorithms for producing ice concentrations and ice type distributions from SAR images to enable the implementation of this capability during the ERS-1 program. This panel calls itself the Radar Age/Type Algorithm Group (RAGTAG). The Ice and Oceans panel will also review the situation of algorithm development for surface wave products with the SAR configurations of the ERS-1 and J-ERS-1 systems and will recommend, if appropriate, the science objectives and resulting data processing needs for a program of wave observations at ASF.

8.2 Ice and Oceans

In the application of ASF data to the study of ice-covered oceans within the ASF station mask, there are a number of prelaunch research tasks which should be performed in order to ensure the timely and orderly analysis of the data. Some of these activities call for aircraft SAR data to be discussed below. The Ice and Oceans Panel recommends that the following research and development be undertaken:

1. Ice motion and classification routines should be refined and further tested, and the use of combined C-band images from ERS-1 and L-band images from J-ERS-1 needs a thorough theoretical examination on a feature-scale basis.

2. Procedures for both detecting and monitoring of the propagation direction and wavelength of ocean swell in the open sea and in the ice near the ice margin should be further developed using spectral analysis techniques based on accepted models of imaging mechanisms.

3. For mission planning at ASF, the climatology of ice motion must be examined so that past and future locations for imaged floes can be estimated. This can readily be done by analysis of Arctic Buoy Program data.

4. The SAR signal resulting from the presence of entrained sediment in the ice of the

coastal regime should be determined.

8.3 Land Processes

To support Land Processes research in the period leading to the launch of ERS-1, several research programs should be undertaken to make ASF data more useful to the scientific community. The Glaciology Panel has pointed out that the application of SAR to glaciology is at a relatively early stage of development and that much remains to be learned about the basic interactions of radar with the snow and ice surfaces of the glaciers before the potential of SAR to glacier studies can be accurately accessed. Nevertheless, work that has been done provides hints that many of the science objectives highlighted in the previous sections can be practically addressed with SAR. Indeed many characteristic features of glaciers have been clearly identified on SEASAT SAR imagery including surficial lakes, crevasses, and moraines. Limited on-site observations on alpine glaciers (Rott, 1884) also reinforce the view that SAR observations of relative backscatter coefficients will allow differentiation between dry snow, wet snow and ice. Glaciological needs for algorithms also include the coregistration and terrain correction of images in a manner similar to the other land programs. Also required are ice motion algorithms similar to those of interest to the polar oceans investigators, but effective on quite different time scales and trackable targets.

Methods for locating pixels to subpixel accuracy are required for multisensor and multitemporal registration. The location correction is essential for terrain correction of SAR and other sensor data. Terrain correction is essential for accurate multisensor and multitemporal data registration. Methods for generation of large scale mosaics are also required.

Techniques for correcting terrain-mapping errors in SAR data are available. The more accurate techniques require digital elevation data at a resolution comparable to the SAR resolution. Digital elevation data at this scale are not available for all of Alaska. These data should be acquired and the terrain correction algorithm should be incorporated into the ASF.

The Land Science Panel emphasizes the requirement for coregistration of SAR data with input image data from moderate and high resolution scanners such as AVHRR, Landsat MSS and TM, SIR, Seasat, and Spot. The coregistration algorithms should also be automatic, or at least have automatic procedure modes available to optimize the repeatability of these analyses. In addition, compression and reconstruction algorithms should be put in place to simplify file transfers. Significant work is still required to generate algorithms and inversion models for derivation of geophysical parameters for radar backscatter. This will require undertaking several well-constrained experiments involving detailed field measurements and coincident SAR coverage.

8.4 Calibration

Minimum radiometric accuracy requirements for the proposed scientific goals have been established and are listed in Appendix A. Relative and absolute calibration of all data products from ASF are required not only for the SAR analysis but also to relate the ASF SAR products to those acquired by other SAR systems and other ERS-1 analyses. Three separate tasks are needed to ensure data product quality as follows:

1. Calibration--defining the absolute and relative accuracy of the end-to-end system in terms of engineering units, e.g., backscatter cross-section;

2. Verification--intercomparison of measurements made by two or more independent sensors, e.g., other SARs or a SAR/Scatterometer, to demonstrate the accuracy of the calibration procedure; and,

3. Validation--comparison of geophysical parameters derived from ASF SAR with those derived by other, preferably standard means.

To conduct Task 1, certain surface data will be required. The three elements of the recommended procedure are:

1. Establish both distributed and point target ground calibration sites within the ASF mask;

2. Conduct a series of underflights with airborne sensors to evaluate the ground sites and the calibration methodology; and,

3. Develop analysis techniques to extract calibration site data from the SAR image, to integrate it with the onboard test equipment data and to install calibration corrections into the SAR processor.

The determination of the overall SAR transfer function calls for known targets on the surface. These should include point targets for establishing the impulse response function and distributed targets to determine the absolute calibration at different "operating points" of the SAR system. The point targets should be both passive devices, e.g., corner reflectors and receivers, and active devices, e.g., polarization-sensitive transponders. The instruments and procedure designs should be coordinated with the ongoing international calibration activities to establish common approaches.

Calibration Sites. It is recommended that a primary calibration site near Fairbanks be established and supported by UAF personnel. An additional secondary site equipped only with passive devices located closer to the projected scientific targets is also required; such a site might be on the North Slope at Toolik Lake. A number of distributed sites should be established, then thoroughly surveyed and evaluated with scatterometers; these should be large, homogeneous and seasonally non-varying.

Airborne SAR Acquisition. Data flights with airborne SARs are necessary to validate the ground instrumentation design and performance and to characterize the distributed targets. These flights should be coordinated with CCRS activities since they will be deploying calibration instrumentation in the Gatineau and Prince Albert masks. Joint campaigns over calibration sites by both NASA and CCRS airborne SAR systems will provide cross-sensor verification of the cross-section measurements and establish the basis for future comparison of SAR data calibrations. In addition the CCRS aircraft carries a C-band scatterometer for a third instrument comparison.

Calibration Analysis. Analysis techniques must be developed to evaluate the calibration data acquired during these campaigns. Additionally, information such as the prelaunch instrument characterization test data and the onboard test equipment measurements must be combined with ground site data to produce the image-correction factors. These corrections must be incorporated into an algorithm which is integrated into the operational SAR processing to ensure that the data products generated during the routine operations of ASF will meet the calibration requirements of Appendix A.

8.5 Aircraft SAR Acquisition and Analysis

The scientific community has very little experience with C-Band SAR or scatterometer data; thus, it is necessary in the prelaunch period that scientists determine the exact information content of C-band radar image data in their specific disciplines in preparation for the analyses of data collected by ERS-1. The first step in this procedure is to obtain airborne C-band radar coverage in areas of Alaska for which there are specific observational objectives and for sites which can be properly verified by planned or ongoing surface studies, especially including those of the calibration program discussed in Section 8.4, above. The first such aircraft data sets over Alaska were obtained in March 1988, principally over sea ice, forests, glaciers and permafrost.

Active research projects that need airborne C-band SAR coverage to provide the required premission validation exist in areas of sea ice type and motion, forestry, neotectonics, glacier mass balance and snowcover, aufeis distribution and volcano-ice interactions. Some flight objectives in support of current scientific projects are:

-Assessing the utility of C-band SAR images for tracking of ice features and for ice type determination over the annual cycle in the different ice regimes of the Alaskan waters;

-Examining the characteristics and accuracy of wave imaging on C-band SAR;

-Determining the sensitivity of C-band SAR to forest conditions and structures over the seasonal cycle in both the biosphere and the basement;

-Assessing the neotectonism relative to the plate tectonic history in accretionary terranes - eastern interior basins;

-Analyzing the mass balance of glaciers through observations of changes in the size of ablation areas in the Wrangell Mountains and portions of the Alaska Range;

-Assessing the usefulness of SAR observations of volcano-glacier systems and interactions in the Wrangell, Tordrillo and Chigmit Mountains (West of Anchorage);

-Comparing the roles of glaciated and unglaciated drainage basins in arctic hydrologic regimes;

-Determining the growth rate and climatic implications of Quarternary volcanic areas;

-Determining the relationships between terrain wetness, roughness and physiography to arctic coastal and fluvial processes;

-Evaluating the backscatter properties of wet and dry glacial snow and firn and of glacial features such as crevasses and lakes; and,

-Microwave penetration into frozen ground and permafrost.

The need for C-band SAR data from aircraft is widely recognized; it is the greatest single need in the prelaunch ASF period. The scientific objectives for research flights with SAR-equipped aircraft have been discussed by both NASA and non-NASA scientists. Additional considerations concerning flight programs are the definition and designation of surface sites of use to the maximum number of investigations, the calibration requirements for the airborne instrumentation and the acquisition of auxiliary data (e.g., Landsat).

9. CONCLUSIONS

This document contains the recommendations of the Prelaunch Science Working Team, or PSWT, of the Alaska SAR Facility (ASF) Program regarding preparation for the science investigations that will be carried out during the initial period of data reception and processing, called Phase 1, when SAR data are being received and processed from the ESA ERS-1 satellite. These recommendations were discussed and assembled at a meeting of the entire PSWT on July 13-15, 1987, at Chena Hot Springs, Alaska and at later meetings of PSWT panels which addressed specific program elements. The PSWT approach was to review the scientific work likely to benefit from the ASF Phase 1 data and to begin developing specifications of the objectives of and approaches to the study of those scientific issues. This discussion led naturally into a detailed listing of the program developments necessary for the successful conduct of the work. These program developments must be accomplished or initiated in the period prior to effective utilization of the ASF Phase 1 data and thus must be pursued immediately as the launch of ERS-1 is only two years away.

The PSWT recommendations also focus on the data processing required to convert the imagery routinely generated by the SAR Processor System into geophysical information, on the archiving support required by the Science Working Team so that it can effectively access the SAR data and the information derived from it, and on the prelaunch research, including aircraft SAR data acquisition, that is needed to improve the interpretation of the satellite data. Specific recommendations are listed below.

Prelaunch Science Working Team Recommendations

Specialized and Interdisciplinary Geoscientific Investigations. The specific investigations to be included in the ASF project should be chosen, and the Science Working Team composed of the PIs of the investigations should begin the preparation for utilizing the ERS-1 SAR data. The preparation time is already short for assembling the software needed to process the SAR images and for arranging for other-platform data acquisition and analysis and field work.

SAR Data of Selected Areas, Times. The selected investigators that constitute the SWT will need access to ERS-1 data scheduling. The iterative task of merging needs for data so as to optimize the limited amount of data should begin as soon as possible.

Precision Processing. The SAR data collected must be processed with high geolocation accuracy (<500 m absolute) and minimum distortion (<0.2%).

Calibration. The SAR image data needs to be calibrated to 1 to 2 dB relative and long-term to accomplish the key temporal studies.

Registration and Projection. The facility, or the investigators individually, need the capability to transfer the images into the map projections used by the specific scientific investigations.

Terrain Correction. Terrestrial sciences need the capability of making terrain corrections to the SAR images; some analysis, e.g., stereo pairing, is done on uncorrected images.

Routine Image Analysis. Some image analysis should be available at ASF on a routine basis. This is especially the case when uniformity is required among a number of investigators, or when the processing required is computer-intensive. The capability should be in place at ASF to support the operation of specialized image processors, such as for ice motion and type analysis, when the proximity to the archive is critical to operation.

Special Purpose Image Analysis. Special purpose image analysis capability must reside either at ASF or at investigators institutions. The capabilities needed include coregistration of SAR and other-platform data, e.g., from Landsat or aircraft, geocoding of SAR data to various grids, mosaicking, change analysis, stereo analysis and general classification.

Aircraft Data With Supporting On-site Observations. Aircraft SAR and other observations, notably areal photography, are essential preparation for analysis of ERS-1 SAR data. The aircraft data are critically needed as they can be controlled as to time, location and azimuth, they have high resolution and they can be obtained in the near future. The aircraft deployments must be scheduled well in advance to allow planning of appropriate on-site data acquisition.

Backscatter Modeling. Theoretical analysis of the nature of backscattering from natural surfaces should be conducted on a cross-disciplinary as well as specialized point of view to facilitate the overall increase in understanding of the SAR data itself.

Preparation for Follow-on Missions. Timely preparations for reception, processing and analysis of data from J-ERS-1 and RADARSAT are needed to supply valuable time-series data.

The scientific benefits of full implementation of the Alaska SAR Facility Project have been examined and have been found to be extensive and significant. Much work has already been done in the specification, design, implementation, testing and planning for the facility itself. This work has been a fine beginning for the scientific utilization of ERS-1 SAR data as well as the data from the Japanese ERS-1 and Canadian RADARSAT instruments. At this point the final steps need to be taken to ensure success. These steps are essentially the establishment of approved scientific investigations and the implementation, at ASF and at investigators' home institutions, of the capability to convert radiometrically correct SAR images into geophysical information by a combination of process modeling, aircraft and surface data analysis, backscatter modeling, image manipulation and image analysis. The tasks are well-defined, and the technology is essentially ready; all that is necessary is the decision to go forward.

Finally. The final PSWT recommendation is: Move forward with this program at the most rapid reasonable pace.

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APPENDIX A. SYSTEM REQUIREMENTS

The complete ASF (Alaska SAR Facility) consists of the Receiving Ground Station (RGS), the SAR Processing System (SPS) and the Archive and Operations System (AOS). The requirements specifying their design and implementation are presented below.

A.1 RECEIVING GROUND STATION REQUIREMENTS

The Receiving Ground Station (RGS) requirements address capability and reliability as shown in summary form in Table A-1. The system must be capable of receiving and recording SAR signal data from ERS-1 and J-ERS-1 in such a way that the changes needed for Radarsat are minimal. The data rates called for to support the scientific program total about 40 minutes per day from ERS-1, J-ERS-1 and Radarsat. International agreements for the use of the ASF may call for additional data to be recorded and transmitted, in raw or processed form, to other investigators. Due to the nature of satellite coverage the RGS must be capable of operation for 24 hours per day, 365 days per year.

The reliability of the RGS must be appropriate to the support of scientific programs, especially to those with extensive data requirements such as the study of sea ice dynamics. For this support 95% of the scheduled data must be successfully recorded. Clearly, occasional difficulties will cause the RGS to be unavailable to record data. The longest continuous period for which the RGS can be unavailable is about 3 days owing both to the problems of rescheduling the data passes and to the need for successful data acquisition scheduling driven by seasonal change, ongoing field programs, and analysis of sequential images for ice studies.

TABLE A-1: ASF SCIENCE REQUIREMENTS

Receiving Ground Station Capability
1.1-1 To acquire and receive ERS-1 and J-ERS-1 and be readily upgradable for RADARSAT
1.1-2 To record a total of up to 40 minutes/day SAR data from all 3 satellites
1.1-3 To be capable of operation for up to 24 hours/day, 365 days per year or at least 3 years beginning with the launch of ERS-1
Receiving Ground Station Reliability
1.1-4 Best effort at successful recording of 95% of scheduled, transmitted data
1.1-5 Best effort to make the longest continuous down interval not to exceed 3 working days

A.2 SAR PROCESSING SYSTEM REQUIREMENTS

Data to be Processed. The system is to be capable of acquiring and processing SAR data from ERS-1, J-ERS-1, and RADARSAT. The data volume from these three programs specify the primary processing requirement; at this time this requirement for science support is estimated to be 5 minutes per day from ERS-1, 10 minutes per day from J-ERS-1 and up to 25 minutes per day from RADARSAT. The RADARSAT and J-ERS-1 data are planned to consist of both real-time data and taped data which may be downlinked simultaneously. The processing of RADARSAT data is more complicated than for the other two instruments because of the number of modes in which the instrument can operate. The SAR Processor System requirements are summarized in Table A-2. The secondary requirement of the SPS is for an additional 10 minutes per day consisting of 3 minutes per day for reprocessing of archived data and data from other receiving stations recorded for NASA-selected Principal Investigators plus 7 minutes per day of catch-up capability to accommodate RGS and SPS intervals of inoperation.

System Reliability. It is recognized that the SPS will experience unplanned downtime due to operational and system problems. For scientific purposes, the key requirements are (1) for data processing to be done on a fixed, low-backlog basis and (2) for data availability to be consistent with availability of key ancillary data for the scientific investigations. These call for 95% of the recorded data to be processed into images within 72 hours of reception and for the longest interval during which the SPS is unavailable for processing to be 3 days.

Products. Three kinds of image products are required from the SAR processor: 4 looks with 30 m resolution (called "Full-resolution"), 1 look complex with a resolution of about 8 m (uncorrected), and a reduced resolution image of about 60 looks and 200 m resolution called "Lo-res" data. SPS processing capability requirements are all data at Lo-res, all data at Full-resolution, and a small amount, approximately 1 quarter of a scene per day at 1-look.

For all ASF products there is a requirement for preserving the maximum swath width possible in the SAR image data. This requirement stems from all geophysical applications of SAR data because the likelihood of successfully observing a target of interest is directly proportional to the usable swath width.

The application of the Full-resolution data is in locating, identifying and evaluating geophysical properties of features of dimensions close to the resolution scale. Such features for sea ice are leads, ridges and oceanic swell; leads are typically 10 m wide while the size of the leads which contribute most to the total open water is some 30 m across (Hall, 1980).

Full-resolution data are required in all terrestrial applications. Examples include experiments in mapping and in the analysis of tectonic and volcanic terranes, and Quaternary geomorphology in fluvial, coastal and periglacial environments. Full-resolution is also needed in studies of hydrology and terrestrial ecology where small features must be observed (see e.g., Shugart and West, 1980). Some examples include measurements of soil moisture, evapotranspiration, extent and condition of snowcover, distribution and condition of wetlands, biomass and variability in gross primary production. For maximum utility in many experiments in geology, hydrology and terrestrial ecosystems the SAR images should be geocoded to a standard map projection, corrected for terrain-induced errors, mosaicked and calibrated radiometrically (see Kwok et al., 1987).

The second output product requirement for the SPS is for 1-look complex (i.e., I & Q) images of selected partial scenes (about one-quarter of a full scene per day) needed for studies requiring examination of phase distributions and similar, but still conceptual, applications of SAR data. Complex or 1-look data, although not used in existing SAR sea ice algorithms, contain information not obtainable from standard SAR output images. Specifically, the Doppler signal contained within the complex image data provides target motion information that can potentially be used to differentiate new ice from open water and to detect gravity waves propagating into the ice. Target motion information can also be quite important in a variety of other applications.

The Lo-res data set is designed for use in geophysical applications in which reduced speckle noise is required and in studies not requiring Full-resolution (e.g., studies of sea ice kinetics) and as a standard browse image for both the paper and tape archives. Previous analyses (Curlander et al., 1985; Fily and Rothrock, 1987) have shown that trackable ice features with dimensions of 200 m or larger are common and that it is not possible to reliably track smaller features even though they can often be identified on a specific image. In terrestrial studies Lo-res data are useful in preparing large-area mosaics that typically cover geologic provinces on the order of 1000 by 1000 kilometers and for studies concerning the regional to global-scale distribution and variability of biomass.

Applications demonstrations projects will require most data in Full-res and Lo-res forms, some of which will need to be supplied in near-real-time (for example through the SAR-COM). In addition it is anticipated that some site-specific field activities will require up to two subframe images per day of 1-look complex data.

Radiometric accuracy and dynamic range. Most geophysical applications using the ASF SAR data will require relative calibration of the data and a knowledge of its output images from different passes. Relative calibration is defined as correcting a particular scene (approximately 100 x 100 km) for system effects, e.g., antenna pattern and intensity fall-off with range. Absolute calibration is a correction, making scenes taken at different times comparable; it is also desirable because it would facilitate use of on-site measurements of radar backscatter, σ^o, in geophysical algorithms. In addition, the system needs to have sufficient dynamic range and proper integrated side-lobe ratios (ISLR) in order to detect the desired surface features.

For most terrestrial applications a relative calibration of ± 1 dB is desirable over the lifetime of the facility. For example, studies in hydrology, terrestrial ecology, volcanology, and coastal and fluvial geomorphology require intercomparisons of both successively acquired image data sets and mosaics of large areas. For geologic mapping experiments it is important that the radiometric fidelity across the swath be as uniform as possible, as systematic radiometric drifts greater than 1 dB across an image may obscure the subtle surface details necessary for interpretation of subdued morphology. Relative or absolute calibration is required to accommodate the response of SAR to the full range of soil moisture conditions. Intercomparison of data from different sensors (e.g., ERS-1 and J-ERS-1) requires absolute calibration of ± 3 dB.

The dynamic range for distributed targets in sea ice scenes is approximately 20 dB in order to detect the desired ice types. Terrestrial surfaces also exhibit a wide range of backscatter values and require a dynamic range of at least 20 dB assuming optimum utilization of the programmable 15-dB receiver gain of the spacecraft instrument. Since the ERS-1 flight instrument has a range of -18 dB to +5 dB, the SPS should be capable of maintaining a 20-dB dynamic range.

Performance monitor. In order to radiometrically validate the processor's output image data, a set of synthetic distributed and point targets should be generated. These data can then be routinely processed by the ASF to insure that processor performance has not degraded. To monitor absolute calibration, a test array consisting of corner reflectors, active radar calibrators (ARCs) and distributed clutter patches (i.e., low return areas and roughened surfaces) must be imaged periodically.

TABLE A-2: SAR PROCESSOR SYSTEM REQUIREMENTS

A. SAR PROCESSOR SYSTEM CAPABILITY
1.2-1 Process to standard products 40 minutes per day of SAR data plus normal overhead and capability of catch-up of 200 minutes of SAR data in 30 days. The standard products will have the maximum swath width possible for a given instrument, and will have the image and radiometric characteristics shown below.
1.2-2 Reprocessing of 3 one-minute scenes of SAR data per day to accommodate users requiring improved orbit parameters
1.2-3 Quick turn-around processing of 2 one-minute scenes of SAR data within 6 hours every day
1.2-4 Capability of reading data from HDDT and writing to AOS disk system to supply up to 1 CCT per day to SWT members
1.2-5 Performance monitoring daily including synthetic or real targets covering at least 18 dB in steps of 2 dB

B. SAR PROCESSOR SYSTEM PRODUCTS	
1.2-6 Resolution	All Data at Full Resolution, 4-looks, 30 m resolution, 12.5 m pixel spacing
	All data at Lo-Res, (about) 30-looks and 100 m resolution, 100 m pixel spacing
	1 subscene per day 1-look, (I and Q), about 8 m resolution, natural pixel spacing
1.2-7 Data Form	All Lo-res data, film and electronic archive, 1:2 M scale factor
	All 4-looks data, electronic archive
	8 minutes of Full-resolution data per day, film with 12.5 m pixels, 1:0.5 M scale factor
	All 1-look data, electronic archive
1.2-8 Projection	Selectable polar stereographic or universal transverse Mercator with additional capability to be consistent with flight agencies' practices
1.2-9 Format, Headers and Annotation	Consistent with Flight Agencies
1.2-10 Geolocation	All images complete with earth location information

C. SAR PROCESSOR SYSTEM IMAGE TOLERANCES	
1.2-11 Geometric Accuracy	Image Location ±500 m absolute
	Image distortion (skew + scale factor) ±0.2%
	Quick Turn-Around Data image location ±2 km
1.2-12 Radiometric accuracy and stability:	Desirable ±1-dB long-term absolute and relative calibration
	Maximum ±-2dB absolute and relative calibration
	Integrated Side Lobe Ratio -13 dB or less
1.2-13 Dynamic Range	NRCS of zero to -18 dB with 6 dB SNR minimum

D. SAR PROCESSOR SYSTEM RELIABILITY
1.2-14 Best effort at processing 95% of recorded data into images within 72 hours (three working days) of reception
1.2-15 Best effort to limit the longest down interval to not more than 5 working days

Geometric accuracy. The geometric accuracy of the pixels within an image is the accuracy with which the pixels can be located in latitude and longitude on the earth's surface. The problem is divided into a location error for some part of the image, say the center, and the percent distortion of line segments to other points on the image from that point. Users of ASF data for change-detection analysis in studies on glaciology, volcanology, Quaternary geomorphology, ecology and snow hydrology need resolution-scale accuracy best obtained by feature-tracking navigation; a system accurate enough for these applications needs to have location errors smaller than 25 m. (This kind of accuracy is beyond the routine capability of the available combined instrument and ground systems). For terrestrial applications requiring multitemporal coverage, coregistration of finer than one resolution cell is required in the geophysical processor.

A.3 ARCHIVE AND OPERATIONS SYSTEM

A.3.1 Archive and Catalog

The Overview Requirements for the Archive and Catalog Subsystem (ACS) are shown in Table 6. They are determined by the support needed by the SWT to perform ASF investigations. To optimize its utility the AOS must be fully integrated into the NASA Ocean Data System and the SIR/Eos image catalog. Certain data products can be generated routinely from SAR images in support of geoscientific studies. Examples of such products are ice type and motion data and terrain-corrected SAR images. It is a requirement of AOS to archive these products and to be the primary interface between the SWT and the ASF for all data and information exchanges and requests for past and future data, as shown in Table 6. Table 6 also shows the performance requirements for the AOS.

A.3.2 Mission Planning

Table A-3 shows the requirements for the Mission Planning Subsystem (MPS) which functions in close relationship to the ACS but is in fact principally a tool for ASF operations planning. The requirements for the MPS insure the capability to plan for future data acquisition in a manner designed to optimize the utility of ASF data to the SWT.

REFERENCES

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Fily, M. and D. Rothrock, 1987, Sea ice tracking by nested correlations, *IEEE Trans. Geosci. and Remote Sens., GE-25*, 570-580.

Kwok, R., J. Curlander and S. Pang, 1987, Rectification of terrain induced distortions in radar imagery, *Photogram. Engr. and Remote Sens., 5*, 507-513.

TABLE A-3: ARCHIVE AND OPERATIONS SYSTEM

Archive and Operations System Functions
Catalog of signal data, Images, geoscientific products, and instrument and facility performance and status; access to other NODS nodes
Archive of image and signal data and bibliography of pertinent system, instrument and scientific documents
Point of contact for interactions between SWT and rest of ASF
Browse archive for transmission of images electronically to remote users
Access to SAR image data by Derived Product Systems, to be implemented independently
Media control for ASF including shipment and retransmission of images, signal data, and geoscientific products to Science Working Team, other US agencies, and flight project agencies
Photocopy archive merged with AVHRR, Landsat archive of long standing at UAF
Information center for future data opportunities and data acquisition control for SWT data requests to be incorporated into ASF activity schedule
Archive and Catalog Subsystem Capabilities
1.3-1 Electronic archive for 1-look, Full-resolution and Lo-res images for support of the Science Working Team to be maintained permanently
1.3-2 Catalog of ASF data holdings and a bibliography to be utilized for ASF related literature allowing on-line ordering of ASF products and documents in the NASA Ocean Data System network
1.3-3 Catalog of images consistent with the JPL SAR Data catalog
1.3-4 Electronic browse archive for use by the SWT for a maximum rate of 20 requests per day of Lo-res images and 4 requests per day each of up to 4 segments of a Full-resolution image
1.3-5 Design permitting access to image data for Derived Products Systems to be designed and implemented later; data flow of 2 Full-resolution images and 20 Lo-res images per day
1.3-6 Access to SAR Full-resolution and Lo-res data for an image analysis workstation to be independently implemented by UAF and located near the AOS; data flow of 2 Full-resolution images per day
1.3-7 An archive of Lo-res and Full-resolution images on film
1.3-8 Distribution of output data in CCT or 5 1/4 in. optical disk to Science Working Team members
1.3-9 A long-term archive for SAR signal data to be maintained permanently
Archive and Operations System Performance Requirements Summary
1.3-10 Best effort to ensure that film data products are prepared and mailed to PIs within 10 working days of reception of request
1.3-11 Best effort to ensure that output products requested through the Catalog prepared for mailing within 3 days for up to 10 computer compatible tapes or 5 1/4 in. optical disks per day throughput
1.3-12 Best effort to provide Availability to the Science Working Team of 95% with the longest down-period not to exceed 5 working days with a 30-day catch-up period.
1.3-13 Communication means to acquire and supply to the SWT available information relating to status of satellites, instruments and the ASF
Mission Planning Subsystem
1.3-14 Propagate and map-display orbital and sensor ground tracks
1.3-15 Determine site-viewing opportunities to accuracy of 10% of swath incorporating parameters of spacecraft, sensors and ASF reception mask for 2 SWT queries per day
1.3-16 Tools for scheduling of data acquisition requests and for assisting the ASF Station Scientist and Operations Manager in the resolution of conflicts within the station mask
1.3-17 Support ASF SWT mission schedule information needs

APPENDIX B: SYSTEM DESCRIPTIONS

B.1 Receiving Ground System (RGS)

The major components of the Receiving Ground Station or RGS are the reflector and antenna pedestal, feed, low-noise amplifier, downconverters and local oscillators, signal demodulators, bit synchronizers, tape recorders, general purpose and pointing computers, tracking receiver, servo electronics, servo drives, time code generator, time standard, data display, and special purpose test equipment. A 10 m reflector will be used with a single channel X-Band and S-Band monopulse tracking feed and an uncooled GaAs FET preamplifier. The feed will be Cassegrain-mounted. Two downconverters will be provided to allow for simultaneous reception of two X-Band channels. This will provide for reliability through redundancy and will also provide the capability needed later to receive two different channels from Radarsat or J-ERS-1. The electronics through the downconverters will be located on the antenna structure. The tape recorders will be in a shared array for use by all the ASF components. The antenna will be located on top of the Elvey Building on the campus of the University of Alaska-Fairbanks.

B.2 The SAR Processing System

The SAR Processing System or SPS takes raw SAR data collected by the Receiving Ground Station (RGS) subsystem from the various SAR sensors (ERS-1, J-ERS-1, and RADARSAT) and converts them into a variety of SAR image data products to be delivered to the Archive and Operations System (AOS). The SPS consists mainly of a SAR data processor and a collection of data input and output devices. A brief description of the SPS including data flow, data processing algorithm, data processor architecture and capabilities follows.

SPS Data Flow. The SPS receives raw SAR data on High Density Digital Tape (HDDT). The data are played back on a High Density Digital Recorder (HDDR) directly into the SAR processor. The SAR processor is capable of deriving the necessary processing parameters from the raw SAR data and the engineering data embedded in the input data stream. The output geolocated image data is merged with the appropriate annotation (created by the SAR data processor) and recorded on selected output devices. These output image products are then delivered to the Analysis and Archiving System for archival and subsequent distribution to the users.

SPS SAR Processing Algorithm. The heart of the SPS is the SAR data processor. To match the anticipated demand of image throughput and fidelity on the ASF, a modification of the Advanced Digital SAR Processor, called ADSP-Mod, has been selected as the SPS SAR data processor. The ADSP-Mod utilizes an algorithm proven through Seasat and SIR-B. The raw SAR data on tape (HDDT) is in sequential range echo format. Each range echo, in the across-track dimension, is compressed by a cross-correlation process. This cross-correlation is done in frequency domain via a forward FFT, a range-reference multiplier, followed by an inverse FFT. The range-compressed data, still in sequential range-line format, is then rearranged so that it is easily accessible in the azimuth direction (the along-track dimension) for cross-correlation with the appropriate azimuth reference functions. Again, the cross-correlation is performed in the frequency domain for high efficiency. The resulting range and azimuth compressed data are then formatted and recorded. Range migration effects resulting from peculiarities of the target-sensor range history (including earth rotation effects) are compensated for in the frequency domain to maintain high computational efficiency and image fidelity. Multilook processing is performed by dividing the available azimuth processing bandwidth into a number of subspectra (looks) and performing azimuth compression on each subspectra. The corresponding azimuth-compressed image data from each look originate from different azimuth areas located at a given range. These looks are then summed incoherently to provide multilook imagery at reduced resolution and with reduced speckle noise.

Geometric and radiometric compensations are applied to the output image data to enhance image fidelity. Autofocus and clutterlock techniques are employed to adaptively update the processing reference functions to maintain a high resolution and signal-to-noise ratio.

SPS SAR Processor Architecture. The ADSP-Mod is a high throughput SAR data processing system composed of a combination of commercial and custom digital processing, communications, and I/O equipment. The custom hardware includes an input interface with buffer memory, a FFT module, a complex multiplier module, a corner-turn memory, an interpolator, and I/O communications processors. Briefly, the ADSP-Mod handles the high computation rate processes (like FFT, reference multiply, and interpolation) with a set of dedicated custom high speed hardware while the lower data rate functions (like processing parameter generation, multilook formation, and image data corner-turning) are delegated to commercial hardware. This architecture affords a high system throughput and yet maintains some degree of flexibility.

B.3 The Science Working Team

The ASF Program will have a Science Working Team (SWT); its members will be chosen through peer-review and selection of proposals submitted in response to one or more solicitations in the form of Space Science and Applications Notices. In the period prior to launch the there will be a Preliminary Science Working Team (PSWT) consisting of representatives of research investigations which require significant preparation or which could contribute materially to ASF implementation. Members of the PSWT and SWT will be investigators responsible for studies utilizing SAR data in geophysics. The objectives, approaches, and expected results of all the selected investigations will be published within a year after the Science Team is formed. The Science Team will be chaired by the Task Scientist and will meet regularly.

B.4 The Archive and Operations System (AOS)

The charter of the Archive and Operations System (AOS) is to support the Science Working Team by providing image and geophysical products and mission planning capabilities. The AOS is divided into the Archive and Catalog Subsystem (ACS) and the Mission Planning Subsystem (MPS). The AOS functions include cataloging, archiving, mission planning, data copying and data dissemination. The summary of data products handled by the AOS is in Table B-1.

In general, Science Team members do not deal directly with the Mission Planning Subsystem. Data Acquisition Requests, called DARs, will be submitted on the ACS computer and transferred to the MPS. MPS also provides specific site coverage analysis, through the ACS, to the Science Team. In this case, the Science Team members will deal directly with the Mission Planner. Science Team members will deal only with the Archive and Catalog Subsystem of the AOS. This subsystem will catalog the contents of the Long Term Signal Archive and all image and geophysical data products of the ASF so that an investigator can locate, evaluate, possibly preview, and order any of the products. Reprocessing of SAR level 0 data will be requested through the catalog. When a data product is to be sent to an investigator, it will go through a media converter to write the product into a readily usable form (e.g., CCT or optical disk). A data compressor will be used to reduce the data volume of the images such that they may be electronically sent to and decompressed at the PI's institution. Thus the AOS will provide ASF investigators with a timely source of image and geophysical products in a readily utilizable form.

C-2

TABLE B-1: AOS SYSTEM

SAR DATA PRODUCTS						
LEVEL	PRODUCT	GENERATION	RETENTION	ARCHIVE MEDIA	DIST. MEDIA	DESTINATION
0.0	Signal Data	Always	Forever	HDDT	HDDT	ESA UK PAF
						NASDA EOC, CCRS
0.5	CCT Signal Data	On Demand	Never	HDDT	CCT,5.25 DOD	SWT, ASF Team
1.0	Complex	On Demand	Never	HDDT	CCT, 5.25 DOD	SWT, ASF
1.5a	Full-Res	Always	Forever	HDDT	CCT, 5.25 DOD	SWT, ASF
					File Trans.	GPS, IIAS
					HDDT	SARCOM
		On Demand	Forever	Film	Film	SWT, ASF
1.5b	Lo-Res	Always	Forever	12 DOD	CCT, CDROM	SWT, ASF
					File Trans.	GPS, IIAS, SARCOM
					HDDT	SARCOM
				Film	Film	SWT, ASF
1.5c	Compr. Full-Res Seg.	On Demand	Never	none	FileTrans.	SWT, ASF
	Compr. Lo-Res					
1.5d	Ave. Compr. Lo-Res	Always	Forever	Mag. Disk	FileTrans.	SWT, ASF
1.7	Geocoded Full-Res, Lo-Res (standard)	On Demand	Forever	12 DOD, Film	CCT, 5.25 DOD, Film, File Trans.	SWT, ASF, GPS, IIAS
3.0	Ice Motion/Class	Always	Forever	Mag. Disk	CCT, 5.25 DOD, Film, File Trans.	SWT, ASF IIAS
3.0, +	Other Geophysical	TBD	TBD	TBD	CCT, 5.25 DOD	SWT, ASF

Where:

CCRS; Canada Centre for Remote Sensing

CCT; Computer Compatible Tape

CDROM; Compact Disk Read Only Memory

DOD; Digital Optical Disk

EOC; ERS-1 Operations Center

GPS; Geophysical Processing System

HDDT; High Density Digital Tape

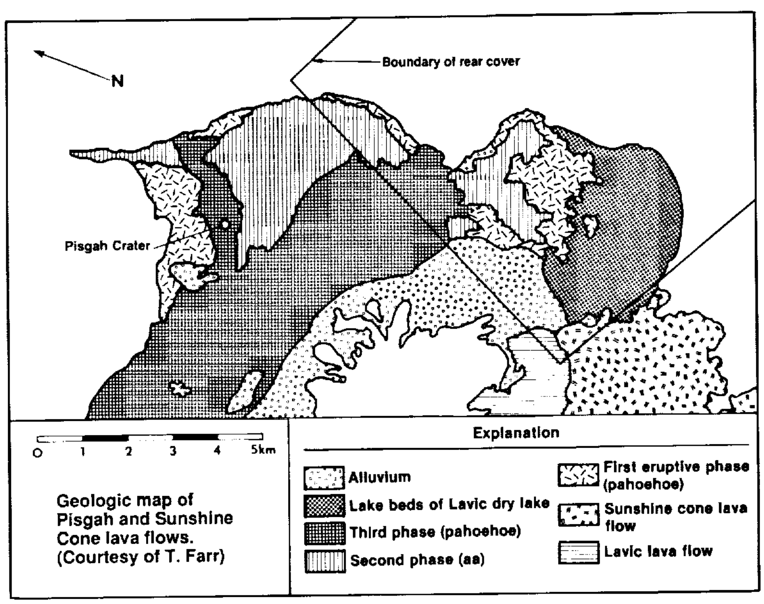
IIAS; Interactive Image Analysis System (UAF)

SARCOM; SAR Communication System (NOAA)

UK PAF; U. K. Processing and Archiving Facility

COVER FIGURE CAPTIONS

Front Cover: *Color-classified aircraft SAR image of sea ice in the Beaufort Sea region of the Arctic Ocean.* This aircraft image of sea ice, taken by the JPL SAR at C-band frequency with VV-polarization, has been quantitatively classified using a clustering algorithm under development at the Jet Propulsion Laboratory (JPL) for the Alaska SAR Facility Geophysical Processor System. This ice classification algorithm first produces an unsupervised segmentation or clustering of the ice image based upon the variation of radar backscatter strength. A comparison of the statistics of the clusters is made with an empirically derived table of radar backscatter signatures of various ice types; this results in an assignment of an ice type to the matching cluster. This image is a combination of the color-classified image and the original image with the following classes: red is multiyear ice, green is thick first-year ice, and blue is thin first-year ice. This classification algorithm, together with a separate algorithm for deriving maps of ice velocity, will provide geophysically useful ice products on a routine and automatic basis for data from the SAR missions to be accessed by the Alaska SAR Facility. This image was obtained on March 11, 1988 and is provided courtesy of Benjamin Holt and Ronald Kwok of JPL.



Geologic map of Pisgah and Sunshine Cone lava flows. (Courtesy of T. Farr)

Rear Cover: *Color-classified Image of Pisgah Lava Flow.* This image is a classified C-band aircraft SAR image of the Pisgah Lava Flow area of the Mojave Desert. The image represents about 12 km vertically. There are three phases of lava shown: the very rough, youngest lava is red; the intermediate age lava is green; and the oldest, smoothest lava is blue. The gold-colored area is an alluvial fan, while the dark purple is lavic lakebed. The classification of this image was performed by the maximum likelihood method followed by an adaptive filter. The final image is a combination of the color-classified image and the original image. For a discussion of radar studies of this area, see Theilig, et al. (1989). The image was obtained courtesy of J. Van Zyl and C.F. Burnette of JPL.