

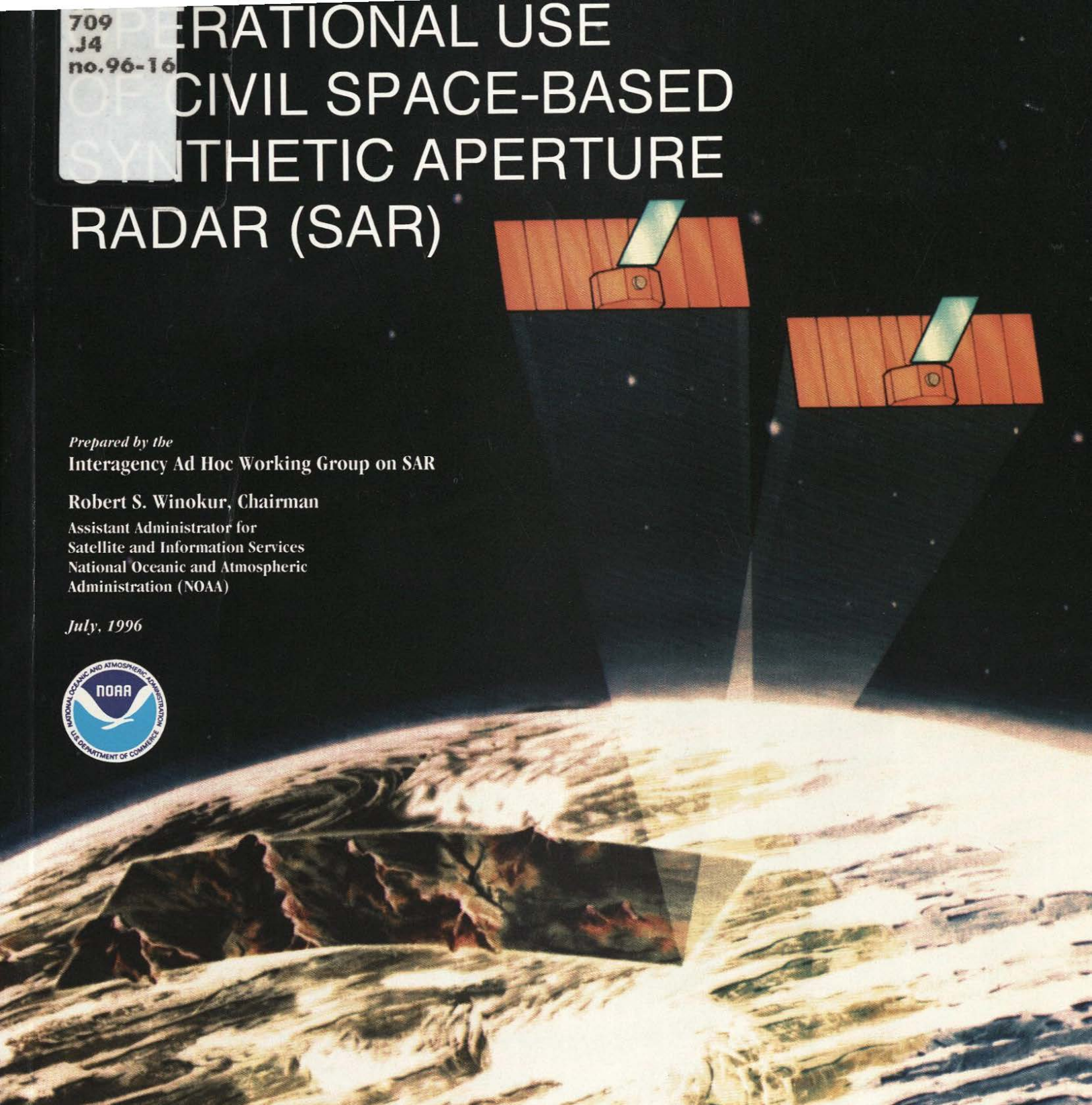
709
.J4
no.96-16

OPERATIONAL USE OF CIVIL SPACE-BASED SYNTHETIC APERTURE RADAR (SAR)

Prepared by the
Interagency Ad Hoc Working Group on SAR

Robert S. Winokur, Chairman
Assistant Administrator for
Satellite and Information Services
National Oceanic and Atmospheric
Administration (NOAA)

July, 1996



Doc.
JPL Publication 96-16

LIBRARY
N C
U S

SEP 27 1996

DEPOSITORY U2444/44

Operational Use of Civil Space-Based Synthetic Aperture Radar (SAR)

Prepared by
Interagency Ad Hoc Working Group on SAR

August 21, 1996

Acknowledgments

This report was prepared by the Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech), for the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data and Information Service and the Interagency Ad Hoc Working Group on SAR. This report is supported by funding from NOAA. The Jet Propulsion Laboratory, California Institute of Technology, compiled the inputs from participating agencies, prepared the graphics, and coordinated the printing of this report. It contains material from contributors in United States government agencies, and graphics material provided by agencies of U.S. and foreign government agencies, universities, and private industry.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government, the National Aeronautics and Space Administration, or the Jet Propulsion Laboratory, California Institute of Technology.

In addition to the many contributors, I wish to especially thank the dedicated team at NOAA, JPL, and the Sidedoor Studio who were instrumental in producing this document.

Robert Chandler
Terri Flynn
Mona Jasnow
Jonathon Malay
Deronda Mayes
Jeffrey J. Plaut
George Shultz
Laura Waag

Donald R. Montgomery, Editor

Preface

The Associate Administrator of NASA for Mission to Planet Earth (MTPE), whose responsibility it would be to develop future U.S. civil SAR satellite programs, has requested the Committee on Earth Studies (CES) of the Space Studies Board (SSB) of the National Research Council to provide a report on the scientific benefits of SAR and has also requested the Assistant Administrator of NOAA for Satellite and Information Services to report on operational applications. Therefore, in a parallel effort to the CES, an Interagency Ad Hoc Working Group on SAR was convened by the NOAA Assistant Administrator in January 1995. This working group was formed to investigate U.S. Government needs and desires for the use of SAR in the execution of their assigned mission areas. The working group has met over a 6-month period and has studied the background on SAR development, scientific results of research SAR missions, and potential opportunities to exploit SAR in the foreseeable future.

This report documents the results of the working group discussions and reflects the contributions of individual members of the group. It is not intended as either a definitive statement of all possible applications of SAR data, nor is it intended to be an official documentation of operational requirements. Rather, it is a close look at what has been learned to date about how SAR may be applied to the solution of real world problems faced by the U.S. Government agencies every day. It describes the functional areas in which the participants believe that SAR has real potential to support operations, and it offers recommendations on how NASA and those federal agencies with an operational need for SAR support, might proceed to demonstrate its value.

List of Participants

- **U.S. Department of Agriculture**

Dr. Thomas Jackson

- **Department of Commerce**

**National Oceanic and
Atmospheric
Administration**

National Weather Service

Dr. Robert Grumbine
Dr. Hendrik Tolman

**National Marine Fisheries
Service**

Mr. Edward Eckhoff
Dr. Thomas Leming
Mr. Brett Schneider

**National Environmental
Satellite, Data and Information
Service**

Cdr. Bruce Arnold
Mr. Jonathon Malay
Mr. William Pichel

Integrated Program Office

Dr. Steven Mango

- **Department of Defense**

U.S. Army Corps of Engineers

Mr. Peter Johnson

U.S. Air Force

Dr. Grant Aufderharr
Major Ben Downing
Cdr. Steven Smolinski

Naval Space Command

Cdr. Tim Barok
Capt. Jeffrey Barron

Naval Oceanographic Office

Capt. Dieter Rudolph
Mr. James Rigney
Mr. William McQueary

National Ice Center

Capt. Larry Warrenfeltz
Cdr. Ray Simmons
Ms. Cheryl Bertoia

Office of Naval Intelligence

Mr. Robert Dunfield
Ms. Patricia Keith
Ms. Viki Medick
Mr. Douglas Schultz

Central Imagery Office

Dr. Peggy Furgerson
Mr. Mitchell Mellen

Defense Mapping Agency

Dr. Jerry Elphingstone
Dr. Randall Smith

- **Department of Energy**

Dr. Patrick Crowley
Mr. Thomas Prevender

- **Department of Interior**

U.S. Geological Survey

Mr. Donald Light
Dr. Larry Pettinger
Mr. William Schoonmaker
Dr. Gene Thorley

- **Department of Justice**

**Drug Enforcement
Administration**

Mr. Robert Fernandez
Mr. Lee Sweetapple

- **Department of State**

Mr. William Erb

- **Department of Transportation**

- U.S. Coast Guard**

Mr. Gordon Barnes
Cdr. William Davidson
Dr. Jennifer Dick
Mr. Larry Jendro
Cdr. Hank Leeper
Mr. Jack McCready
Mr. Jeffrey Sturgess

- **Central Intelligence Agency**

Mr. Joseph Coleman

- **Federal Emergency Management Agency**

Mr. Gil Jamison
Dr. Frank Tsai

- **National Aeronautics and Space Administration**

Mr. Rick Crowsey
Mr. Richard Monson

- **Johns Hopkins University/Applied Physics Laboratory**

Dr. John Apel

- **Caltech/Jet Propulsion Laboratory**

Dr. Diane Evans
Dr. Anthony Freeman
Mr. Donald Montgomery
Mr. Michael Sander
Mr. Merle Veren

- **User Systems, Inc.**

Mr. Walter McCandless

Contents

	Acknowledgments.....	i
	Preface	ii
	List of Participants.....	iii
1	Executive Summary	1-1
2	Introduction	2-1
	a. Rationale.....	2-1
	b. Background	2-1
	c. Purpose of the Report.....	2-2
3	SAR Development.....	3-1
	a. Early Imaging Radar - SLAR	3-1
	b. Seasat SAR.....	3-1
	c. Shuttle Imaging Radar	3-2
	d. European Environmental Remote Sensing Satellite (ERS-1).....	3-3
	e. Japanese Environmental Remote Sensing Satellite (JERS-1)	3-4
	f. Almaz	3-4
	g. Canadian Radar Satellite (RADARSAT).....	3-4
	h. Ongoing Research	3-4
	FIGURES.....	3-6
4	SAR Data Processors - Evolution and Capabilities.....	4-1
	a. Early Processors.....	4-1
	b. Digital Technology	4-1
	c. Hybrid Systems.....	4-2
5	Space-Based SAR Data Access	5-1
	a. Alaska SAR Facility	5-1
	b. National Ice Center	5-1
	c. Access to RADARSAT	5-2
	d. Transportable Stations	5-3
	e. NOAA Satellite Ocean Remote Sensing.....	5-3
	FIGURES.....	5-4
6	Data Costs	6-1
	a. European Policy	6-1
	b. RADARSAT Policy	6-1
7	Operational Applications Development.....	8-1
	a. Need for Demonstration Projects	7-1
	b. New Investments Required.....	7-1
8	Future Initiatives and Opportunities	8-1
	a. SAR-2000	8-1

	b. A Third Space Radar Laboratory (SRL-3) Mission	8-2
	FIGURES.....	8-3
9	SAR Requirements to Support Operations	9-1
	a. Operational Categories	9-1
	b. Assessment Limitations.....	9-1
	c. Data Blending	9-1
	FIGURES.....	9-2
10	Applications	10-1
	10.1 Mapping and Charting	10-1
	a. Definition	10-1
	b. Mapping	10-1
	c. Charting.....	10-2
	10.2 Resource Monitoring and Management	10-2
	a. Definition	10-2
	b. Multispectral Use	10-2
	c. Fire Fuels.....	10-2
	d. Vegetation and Land Cover.....	10-2
	e. Crop Identification.....	10-3
	f. Forest Condition Assessment	10-3
	g. Land Inventories.....	10-3
	h. Mineral Resource Assessments	10-3
	i. Sea Ice and Snow Maps	10-3
	j. Coastal Wetlands	10-3
	10.3 Pollution and Waste Threats.....	10-3
	a. Definition	10-3
	b. Runoff Patterns	10-4
	c. Ocean Transport	10-4
	d. Oil Spills.....	10-4
	10.4 Natural Hazards.....	10-4
	a. Definition	10-4
	b. Volcanic Eruptions and Earthquakes	10-4
	c. Hurricanes.....	10-5
	d. Flooding	10-5
	e. Mines.....	10-5
	f. Forest Fires.....	10-5
	10.5 Oceans, Great Lakes, and Ice	10-5
	a. Definition.....	10-5
	b. Ice Operations	10-5
	c. Littoral Warfare.....	10-6
	d. Search and Rescue	10-6
	e. NOAA CoastWatch	10-6
	10.6 Enforcement and Surveillance.....	10-6
	a. Definition	10-6
	b. Feature and Change Detection.....	10-7

	c. Ships and Ship Wakes.....	10-7
	d. Cueing Tool	10-7
11	SAR Data Processing and Distribution	11-1
	a. Data Processing	11-1
	b. Data Distribution	11-1
12	Satellite Tasking	12-1
13	Training.....	13-1
14	Recommendations.....	14-1

Appendix

A. Acronyms and Terms.....	A-1
----------------------------	-----

1—Executive Summary

Since the flight of the United States Seasat spacecraft in 1978, the capability to collect Synthetic Aperture Radar (SAR) imagery of the Earth's land and ocean features over broad areas, day or night, and under all weather conditions has been established and refined. Using SAR data collected by Seasat, Space Shuttle Imaging Radars, and subsequent European and Japanese satellites carrying similar instruments, researchers have shown that this technology may have significant value in the advancement of science, particularly in understanding the physical characteristics of the planet and the impact of human activity on them. The scientific community has also collected a sufficient body of evidence to suggest that SAR may prove to be extremely valuable in applications which are operational in nature, such as monitoring of agriculture, mapping, resource management, law enforcement, national defense, and environmental observations in support of warnings and predictions. However, except for the expanding use of SAR imagery in ice monitoring by the National Ice Center in Suitland, Maryland, operational use of civil space-based SAR by U.S. Government agencies has been extremely limited. This has been due, primarily, to the lack of easily accessible SAR data, but also to a fundamental lack of understanding by operational agencies of the utility of SAR in possible applications and to the lack of an infrastructure to begin operational use of SAR on a large scale.

This report documents the results of the work of the Interagency Ad Hoc Working Group on SAR, which addressed the operational applications of civil space-based SAR by U.S. Government agencies as a companion and supporting effort to the SAR science study prepared by the Committee on Earth Sciences of the Space Studies Board. It describes the functional areas in which the working group believe that SAR has real potential to support operations, and it provides recommendations on future U.S. Civil SAR initiatives.

Based on input from the participating agencies, this report discusses the potential for SAR to be used in a number of operational mission areas. The following list, while not a complete list of all possible applications, is representative of realistic opportunities which are foreseen for operational exploitation of SAR.

- Mapping and Charting,
- Resource Monitoring and Management,
- Pollution and Waste Threats,
- Natural Hazards Mitigation,
- Oceans and Ice, and
- Enforcement and Surveillance.

While the working group is aware of NASA's austere fiscal environment, the group believes that near-term U.S. investments in advanced civilian space-based SAR systems are a prudent means of exploiting this technology to obtain data of high national priority and enhance the operational capabilities of civil and military missions. The following SAR initiatives are included in the working group recommendations:

- The United States should make the investments necessary to develop, at the earliest possible date, a civilian SAR satellite capability with performance attributes

necessary to support operational applications. Two possible options are recommended:

Option 1: The development of an independent U.S. SAR satellite system.

Option 2: The development of a U.S. interferometric SAR satellite system which can be an element of an international SAR satellite constellation, comprised of SAR systems with a diversity of frequencies and polarizations arranged such that multifrequency, multipolarization data can be obtained from the constellation.

- To exploit near-term opportunities which (1) broaden the use of SAR in operational applications and (2) maintain the momentum and interest of the operational community, the working group recommends that
 - a. Consideration be given to a third flight of the SIR-C/X-SAR sensor configured for interferometric operation, on a Space Radar Laboratory (SRL) mission. Such a mission can acquire global digital terrain elevation data at high accuracy (DTED-2) to support national needs (DOD, DOI, DEA, FEMA) for mapping information.
 - b. The Interagency Ad Hoc Working Group on SAR continues to serve as a forum for Government agency operational users of SAR data, where operational requirements can be further defined and documented, where new applications can be identified and results shared, where SAR activities (aircraft and satellite) can be coordinated, and where SAR research needs and product development requirements of the operational community can be defined for research investments.

2—Introduction

a. Rationale

Synthetic Aperture Radar (SAR) is a remote-sensing technology which uses the motion of the aircraft or spacecraft carrying the radar to synthesize an antenna aperture larger than the physical antenna to yield a high-spatial resolution imaging capability. SAR systems can thus obtain high-spatial resolution geophysical measurements of the Earth over wide surface areas, under all-weather, day/night conditions.

This report was prepared to document the results of a 6-month study by an Ad Hoc Interagency Working Group on the Operational Use of Civil (i.e., non-military) Space-based Synthetic Aperture Radar (SAR). The Assistant Administrator of NOAA for Satellite and Information Services convened this working group and chaired three meetings of the group over a 6-month period. This action was taken in response to a request by the Associate Administrator of NASA for Mission to Planet Earth for an assessment of operational applications of SAR to be accomplished in parallel with a separate study requested of the Committee on Earth Studies of the Space Studies Board of the National Research Council on the scientific results of SAR research missions. The representatives of participating agencies are listed following the Preface. There was no formal charter for the working group or long term plans for future meetings. However, the working group may be reconstituted in the future as a coordination body for multiagency use of operational SAR systems.

b. Background

Since the launch of Seasat in 1978, space-based SAR technology has, through continuing research investments, advanced to a point at which it has become widely accepted that SAR could now be applied to a broad range of operational applications to reap a return on the large investments made in SAR research. In order to affect the transition of the scientific experience base for SAR capabilities into the operational exploitation of U.S. and foreign SAR satellite missions, it became clear that coordination must occur between SAR scientists and government agencies which may have requirements for SAR support. Against this background, the working group was asked to look at how SAR might best be used to solve real operational problems and what actions should be pursued, in the near term, to begin this exploitation effort.

All operational capabilities that require an investment of government funds must, ultimately, be supported by documentation of Operational Requirements and identification of the required funding. For SAR to become an accepted tool in delivering new operational capabilities, government agencies must define those operational requirements which are not satisfied by current and planned space missions and might be satisfied or aided by SAR. These requirements will then serve as the basis for future U.S. SAR missions or, as a minimum, for future operational exploitation of U.S. or foreign SAR missions which are being planned for research or preoperational purposes.

Because of the current fiscal climate, all agencies are being very cautious about their use of the term "requirements" when resources to satisfy them may not be available. Hence, the use of this word in this report is not meant to imply the existence of a formal operational requirement which specifies a documented need for SAR imagery. Instead, presented here are the "needs" or "desires" of the participating agencies for which SAR could be a logical solution. They are described here to illustrate operational applications of

SAR which may, given sufficient operational demonstrations and funding identification, constitute future operational requirements for use of civil SAR satellite systems. For now, however, they should be considered only "Desirements" which, although not validated and funded, are realistic statements of what SAR can do for each government agency which has, what it perceives to be, both a desire and a need for SAR.

c. Purpose of the Report

It is the purpose of this report, therefore, to

- Review the current state of space-based SAR technology from an operational perspective;
- Describe the present infrastructure and data availability relative to prospective operational utilization;
- Examine the current operational SAR needs, as stated by U.S. Government users, which may form the basis for validated and funded operational requirements in the future; and
- Explore the opportunities that may exist to further test the utility of SAR through demonstration projects using data from Canada's RADARSAT and data from a possible third Space Radar Laboratory (SRL) mission.

This report will serve as a companion to the final report to the Committee on Earth Sciences of the Space Studies Board of the National Research Council entitled "Spaceborne Synthetic Aperture Radar: Current Status and Future Directions." Collectively, the two reports should provide managers and decision makers with a balanced view of the need for, and applications of, space-based SAR for scientific research and support to operations.

It is also the purpose of this report to foster dialogue within the interagency working group, as a means of stimulating the definition of an up-to-date, comprehensive set of capabilities for space-based SAR which could meet the operational needs of U.S. Government users. These capabilities would then be used to write the technical specifications and cost estimates as part of creating fully validated operational requirements and full fledged exploitation programs, which would follow.

3—SAR Development

a. Early Imaging Radar - SLAR

The first imaging radars were Side-Looking Airborne Radars (SLARs) developed in the military for reconnaissance purposes. At the wavelengths then used (2 cm), these radars could image the Earth's surface through clouds and atmospheric water vapor under day/night conditions, a considerable advantage for reconnaissance missions. SLAR is known as a "real aperture" radar because its along-track resolution is determined by the size of the physical antenna footprint on the ground, which is given by the ratio of wavelength times the slant range divided by the along-track antenna length—fine resolution in the cross-track direction is obtained through the use of pulse compression techniques. The synthetic aperture radar (SAR) was invented in the 1950s to permit radars to achieve fine spatial resolution in the cross-track direction. As such, SAR's can achieve equal resolution in both directions.

The principal disadvantage of using SLAR is that its along-track resolution is limited by the antenna length. The development of synthetic aperture radar overcame this problem. Like SLAR, SAR used pulse compression techniques to provide fine-range resolution. However, it was shown that if a pulsed coherent radar could be used, then the Doppler-shifted radar returns could be recorded and played back through a coherent SAR image processor to synthesize an along-track antenna length much longer than the antenna's physical length. A further advantage of SAR was that it could be used at longer wavelengths than SLAR.

The first nonreconnaissance uses of these real aperture radars were for cartography and geologic mapping. Radar returns are sensitive to surface structure, surface roughness, surface slope, and the presence of water. Combined with an all-weather capability, this provided geologists with a means to map heavily cloud-covered and previously uncharted regions. Studies were conducted to determine how SLAR images could be used in the emerging field of radargrammetry; i.e., the use of radar images for cartographic and topographic mapping, the functional equivalent to the well established field of photogrammetry. It was also determined that radar images could be used to map different surficial materials, including sand, gravel, and glacial deposits, or to delineate geologic contacts between fans and playas or bedrock and alluvial fans.

b. Seasat SAR

The first space-based imaging radar to be used for imaging of the Earth was the L-band SAR on Seasat (Figure 3-1), one sensor in an instrument suite launched into an 800-km altitude near-polar orbit in June 1978. This horizontally polarized sensor operated at a fixed wavelength (23 cm) and at a fixed-look angle (20 degrees from nadir). The Seasat swath width was 100-km and the resolution was approximately 25 meters. While a SAR was included in the Seasat payload primarily for the purpose of ocean wave imaging, during its 3-month lifetime, radar images also were acquired over large areas of the Northern Hemisphere.

Imagery obtained from the Seasat SAR clearly demonstrated its sensitivity to surface roughness, slope, and land-water boundaries. Seasat images have been used to determine the directional spectra of ocean waves, surface manifestations of internal waves, polar ice-cover motion, geological structural features, soil moisture boundaries, vegetation characteristics, urban land-use patterns, and other geoscientific features of interest.

Seasat also established a commercial demonstration program involving private-sector operational users representing a variety of marine applications, including off-shore oil and gas operations, optimum ship routing, deep-sea mining, commercial fishing, and private weather forecasting. The purpose of this program was to permit operational users an opportunity to test the utility of Seasat-derived measurements, including SAR, in commercial ocean applications. Through a series of retrospective case studies, commercial users were able to show the economic impact of the use of Seasat data in daily operations.

Despite its overall technological and scientific success, Seasat's relatively short lifetime precluded the acquisition of a seasonal data set. Moreover, the Seasat SAR was a single-parameter instrument using a fixed wavelength, polarization, and incidence angle. While the near-nadir incidence angle was ideal for acquiring strong ocean returns, it produced severe geometric layover distortions on terrain images of high-relief regions.

c. Shuttle Imaging Radar

The next space-based SAR to follow Seasat was the Shuttle Imaging Radar-A (SIR-A), launched in November 1981 on board the Space Shuttle Columbia on its second mission. Using the Seasat SAR technology (spare hardware), but with a higher incidence angle of 50 degrees, the SIR-A mission was focused on geological research. SIR-A provided much improved image data for geological analysis that were relatively free of the layover distortions in areas of high relief. SIR-A also led to the discovery of buried and previously uncharted dry river beds beneath the Sahara Desert, thus demonstrating the ability of L-band radar to penetrate up to several meters in hyperarid sand sheets.

SIR-B, the next NASA SAR mission, flown in October 1984 on the orbiter Challenger, also used the Seasat/SIR-A technology, but with an articulating antenna which permitted a variable incidence angle over a 15- to 60-degree range. This first multi-incidence angle data set demonstrated the potential for mapping surface features (particularly forests) using multiple-incidence angle backscatter signatures, and for topographic mapping. SIR-B data were also used to demonstrate the sensitivity of L-band radar images to parameters such as soil moisture, geological, structural, and lithologic features, and oceanic directional wave spectra.

The success of the SIR-A and SIR-B missions, supported by aircraft-based SAR research, led to a second generation SAR design, reflected in the SIR-C/X-SAR instrument (Figure 3-2) on the Space Radar Laboratory (SRL) missions. These two missions (SRL-1, launched April 1994, and SRL-2 launched October 1994) incorporated a multifrequency, multipolarization, variable incidence angle SAR and has provided scientific and applications information hitherto unavailable. The multiparameter capability of the SIR-C/X-SAR radar, coupled with the introduction of routine sensor calibration, opened a new regime in SAR-based scientific investigations and applications. The analysis of data from the SRL missions is only beginning, but initial results indicate dramatic new capabilities only possible with the a multiparameter instrument. Polarimetric data has allowed improvements in soil moisture measurements in bare soil areas and canopy water content estimates in vegetation covered areas. Accurate maps of snow cover and snow water equivalence are now possible to aid in water supply forecasting and hydroelectric power management. Oil spills are detectable and the multiparameter capability permits oil type and oil-natural surfactant differentiation to be determined. Ocean surface waves were measured and, for the first time, wave spectra were processed on-board the satellite for direct downlink to operational centers. Cross-polarization data were proven to be a powerful tool for extracting lithographic information in the interpretation of geologic features. Mud flows on Mt. Pinatubo were observed which posed severe hazards to local populations. Volcanic

ash deposits and lava flows were observed, and, using interferometric techniques, measurements of surface displacement in volcanic areas were obtained. Such measurements offer the potential for predicting volcanic eruptions and producing damage maps following eruptions and earthquakes. Using calibrated cross-polarization L-band data, the aerodynamic roughness of the ground was measured, thus permitting the assessment of the ability of the wind to initiate dust and sand storms. Multiparameter data allowed a determination of wetland inundation (flooding status) and vegetative cover, biomass estimates, crop monitoring, vegetative mapping, and the monitoring of flooded forests and coastal/low-stature wetlands. While many of these capabilities were the result of extensive airborne SAR research, their extension to space-based platforms was confirmed as a result of the SRL missions. More exciting results will surely emerge as data analysis continues.

d. European Environmental Remote Sensing Satellite (ERS-1)

Building upon the Seasat experience, the European Space Agency (ESA) embarked upon the development of the ERS-1 satellite (Figure 3-3). Launched in May 1991, this satellite contains a suite of earth/ocean observing microwave instruments, including a C-band SAR. Like Seasat, the SAR has a single-frequency, single-polarization (VV) and fixed incidence angle (23 degrees). Unlike Seasat, the SAR operates as one mode of an Active Microwave Instrument (AMI) which, in another mode, functions as a wind field scatterometer. In its nearly 4 years of operation, the ERS-1 SAR has proven to be an extremely reliable and stable instrument. The calibrated SAR data have proven to be highly useful in polar ice applications where ice-type determinations are possible using fixed look-up tables. In spite of being a single-parameter instrument, the ERS-1 SAR has provided a rich and extensive set of Arctic sea ice, ocean, and land data. The sea ice data are, for the first time, being used to support ice operations in the national centers of the U.S., Canada, and Sweden. The nearly 4-year life of the SAR has permitted the collection of an extended time series of data over several seasons, allowing long-term and seasonal variations of land features, vegetation cover, and sea ice to be measured.

ERS-1 SAR has been used to monitor flood water levels during the great Midwestern floods of 1993 and detect standing water beneath vegetation canopies. ERS-1 SAR has demonstrated a crop monitoring capability using multitemporal data, and has been effective in studying boreal forests on issues related to the terrestrial carbon cycle. With some limitations, ERS-1 SAR has been effective in mapping wet snow. ERS-1 SAR has established most of the scientific utility for ice sheet and glacier work. It has been a powerful tool in measuring the Greenland ice sheet, where the data clearly define the zonation and boundaries of the surface, based on backscatter signatures. Variations in these patterns can provide an indication of changing input conditions on a near-continental scale. In coastal ocean regions, ERS-1 SAR has measured fronts, eddies and internal waves, and has shown variations in the shallow water seabed topography through surface signature modulations. Images of wave refraction and shoaling have also provided indications of the seabed topography. Surface ships and shipwakes have been regularly detected in the SAR imagery, and operational demonstration projects on vessel traffic monitoring have been successfully conducted. Oil spills have been detected and monitored, and several vessels have been cited by pollution authorities for violations based on ERS-1 SAR observations. ERS-1 SAR observations of sea and lake ice have shown that ice motion, ice age, ice/water boundaries, polynyas, leads, and ridges can be accurately measured. While in the 3-day repeat orbit phases of the mission, ERS-1 SAR has been used in repeat-pass interferometric mapping experiments with good results. However, the 23-degree incidence angle creates severe layover distortion in areas of high relief.

Earlier this year, ESA successfully launched the ERS-2 spacecraft, identical to the ERS-1. The two satellites are being flown in a tandem mode (flying one after the other along the same track) to allow interferometric processing of images from both spacecraft to create topographic maps. While this is being done on a very limited demonstration basis, the results to date show promise for this technique which can be expected to be useful in follow-on multi-spacecraft programs.

e. Japanese Environmental Remote Sensing Satellite (JERS-1)

In 1984, Japan initiated the development of the JERS-1 satellite that was successfully launched in February 1992. The principal sensor in the instrument payload is an L-band SAR with a single polarization (HH) and fixed-incidence angle (35 degrees). The longer wavelength was adopted in order to provide greater penetration of vegetative cover and sand layers, while the relatively large incidence angle was incorporated to reduce the layover distortions in mountainous and high-relief regions. Unlike the Seasat and ERS-1 and 2 satellites, the JERS-1 spacecraft includes two tape recorders that may be used to store SAR data for subsequent playback to selected ground stations. As a result, global SAR data can be acquired independent of a global network of ground stations. Unfortunately, a reduction in transmitter power has limited the use of JERS-1 data.

f. Almaz

Brief mention should be made of the short duration mission of the Almaz radar satellite launched by the Soviet Union in 1987. Almaz was a single-frequency SAR sensor mounted on an extremely large spacecraft derived from SALYUT space station components. Although the Soviet government later shared imagery from Almaz, revealing optically-processed data similar in capability to Seasat, the program was originally shrouded in secrecy (the spacecraft identified only as Cosmos 1870 by the U.S. Space Command). In the new political order of Russia, a follow-on Almaz has been announced as almost ready to launch, and support is being collected by Russia for data purchases which can be used to offset the cost of the program.

g. Canadian Radar Satellite (RADARSAT)

The Canadian Space Agency (CSA) developed RADARSAT (Figure 3-4), which was launched by NASA from Vandenberg AFB, California on November 4, 1995. This spacecraft carries a single-frequency (C-band), single-polarization (VV) SAR which provides a variety of beam selections that can image swaths from 35 km to 500 km with resolutions from 10 meters to 100 meters, respectively. Incidence angles range from less than 20 degrees to more than 50 degrees. This satellite is the first in a continuing series of RADARSAT spacecraft.

RADARSAT is operated as a quasi-commercial program, with the Canadian Government paying for the development and operation of the spacecraft and a private company, RADARSAT International (RSI), will market data with its revenue helping to defray the cost of operations and production.

h. Ongoing Research

Over the ensuing 16-plus years since the launch of Seasat, space-based SAR technology has evolved to a powerful, but still developing level. More scientific research is needed to understand the radar phenomenology involved with some microwave-surface interactions, from which refined and robust algorithms will emerge to permit more accurate measurements of geophysical parameters. The advent of multiparameter SAR and

interferometric techniques permit vast new measurement capabilities that can make space-based SAR an ever more powerful remote sensing tool, supporting both scientific research and operations. The experiences to date with ERS-1, ERS-2, JERS-1 and the SIR-C/X-SAR missions, have provided the learning experiences for operational users to develop the skills needed to use SAR data from the satellites to be available over the next decade in support of operational applications. Unlike scientific investigations, operational applications need not have perfectly refined algorithms or data extraction techniques in order to achieve operational utility. In many areas, such as ice operations, coastal zone and wetlands monitoring, flood water level monitoring, fisheries management and enforcement, and oil spill detection and monitoring, the SAR technology, based on single parameter SAR, is sufficiently mature to make operational investments now in data acquisition and utilization useful and cost-effective. Both single and multiparameter SAR systems can yield geophysical measurements under all-weather, day/night conditions at high-spatial resolution over wide surface areas—a unique aspect of this sensor technology. Continuity of data is a major requirement of operational users, which dictates that a series of space-based SAR systems must be approved and launched over a decade or more time period. The current number of approved future SAR missions shown in Figure 3-5 begins to ensure this continuity of data and is sufficient to justify operational investments.



Figure 3-1. The Seasat satellite, launched in 1978, carried the first civilian synthetic aperture radar into space. (Photo: NASA)

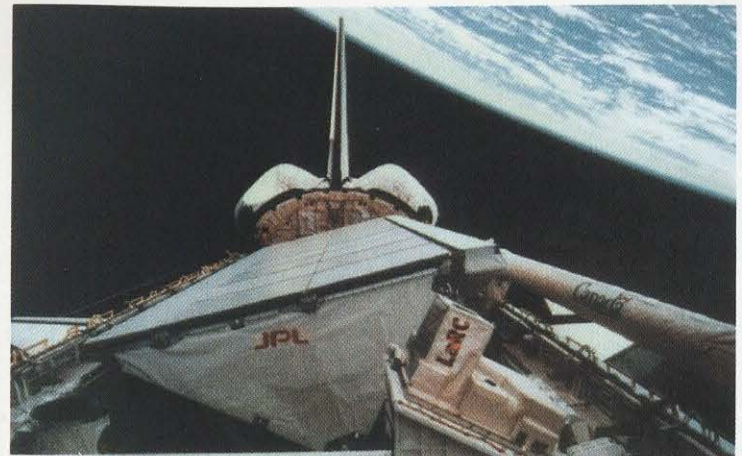


Figure 3-2. SIR-C/X-SAR, the most advanced imaging radar system to have flown in Earth orbit, launched aboard the space shuttle in April and October 1994 as part of NASA's Mission to Planet Earth. (Photo: NASA/ Johnson Space Center)



Figure 3-3. The European Space Agency ERS-1 satellite, launched in 1991, carries a C-band synthetic aperture radar for Earth and ocean observations. (Photo: European Space Agency)

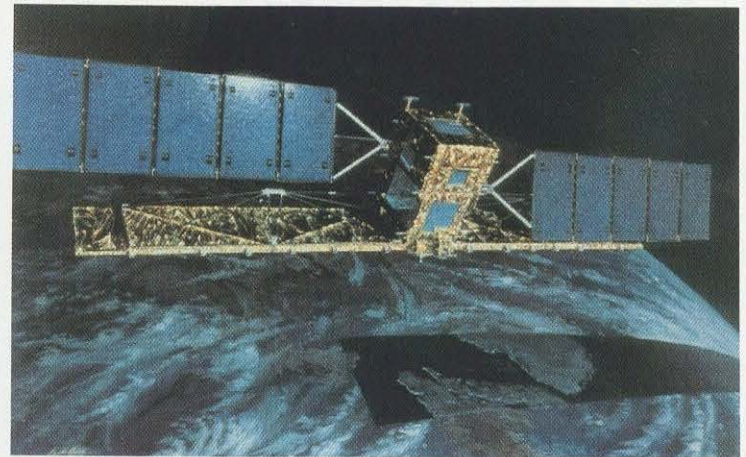


Figure 3-4. RADARSAT, launched in 1995, the first Canadian remote sensing satellite, carried a C-band synthetic aperture radar with a steerable antenna and variable swath width capability. It is the first operationally-oriented commercial radar satellite. (Photo: Canadian Space Agency)

CIVILIAN SAR SATELLITE PROGRAMS

CURRENT, APPROVED AND PLANNED

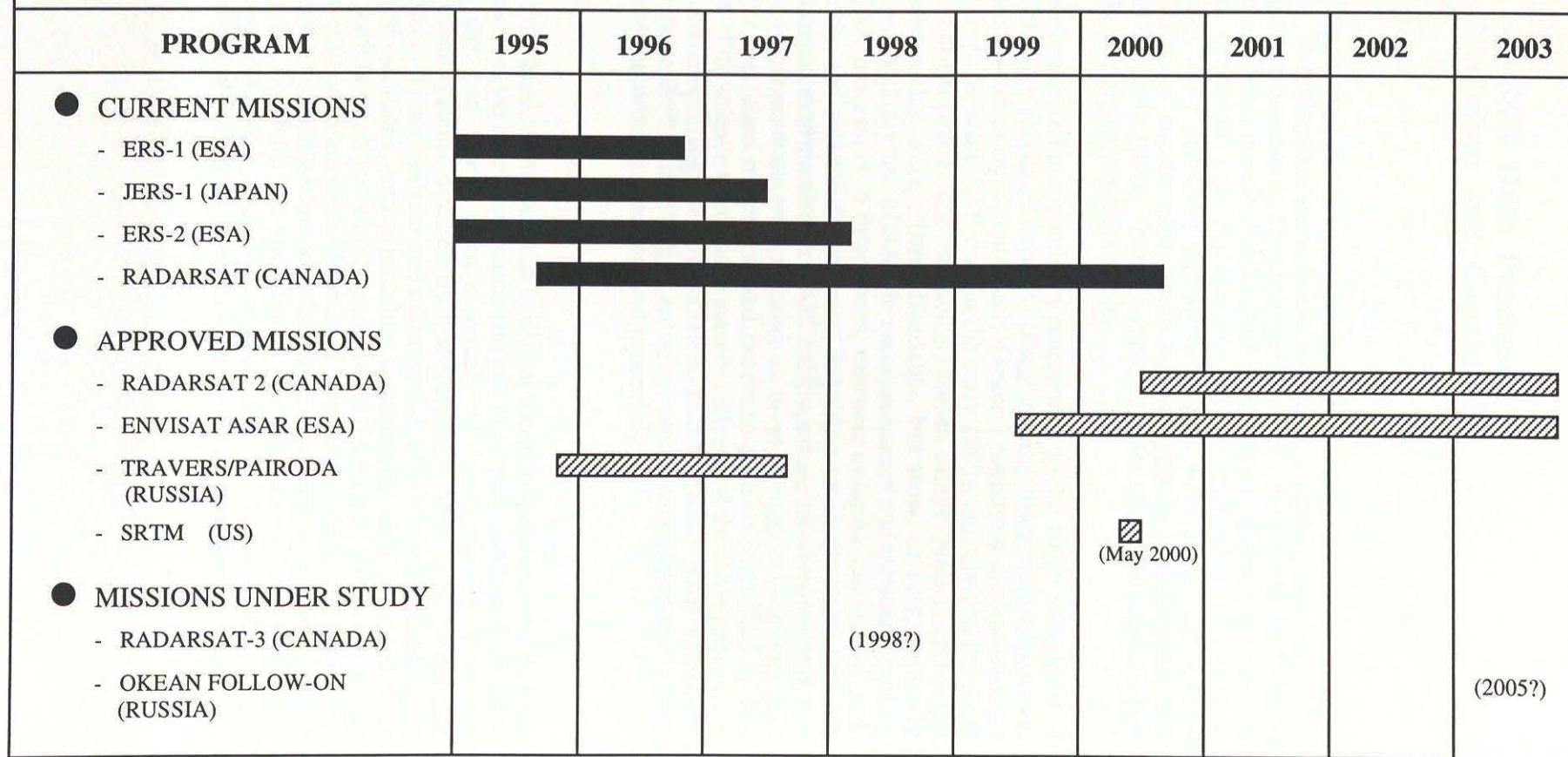


Figure 3-5

4—SAR Data Processors - Evolution and Capabilities

a. Early Processors

The creators of SAR discovered that they had given birth to a data processing problem of Herculean proportions. To realize fine cross-track resolution, a signal processor had to perform significant correlation processing for each image pixel. Among the techniques considered to meet this challenge were electronic analog and digital systems arranged in architectures never before attempted, and optical computational techniques, also in their formative years. Although some primitive digital techniques were attempted, optical methods became the solution of choice, and, while falling short in performance, this technology prevailed until the early 1980s when the rapid advance of digital technologies made the transition to fully digital processors possible.

Digital SAR processors appeared in the military community in the 1970s in support of aircraft applications. While they produced superior image quality, they were expensive, customized designs. Optical systems remained faster. General purpose digital processors began to be used to process space-based SAR data in the early 1980s, and divided the SAR processor world into fast optical processors that compromised image quality, and high-image quality digital systems that were either affordable, but slow, or fast, narrowly defined and very expensive. Military use of SAR in reconnaissance and tactical targeting applications has driven SAR processors to distributed, user-site systems, capable of real-time throughput. Currently, the science community, requiring more diversity in SAR sensor design and applications (multiparameter SAR, multiaperture interferometers), has been content with selected frame products and extensive archives to support multiyear data analysis activities. They have relied on centralized processing assets identified with a particular radar or project. The science users have greatly influenced the SAR processors used in the ground stations supporting the ERS-1, ERS-2 and JERS-1 SAR satellites. These processors, at best, have limited throughput capacity, which severely restricts their use in supporting operations requiring fast turnaround processing.

b. Digital Technology

Over the last decade, the massive investment in digital technologies has provided the tools needed to create practical systems that match the needs of users and modern SAR systems. Today, designers can select from a variety of commercially available workstations, multi-processor systems directed by a workstation, super computers and massively parallel computers. These systems use commercial, off-the-shelf technologies with few or no customized additions, and affordable, commercial high-level software which can handle a wide variety of airborne and space-based SAR data. Software is also available that allows the user to calibrate the SAR images in intensity, phase and geometry, as well as range cell migration corrections and auto focusing, all of which may be required by multiparameter data sets. For both the operational user and scientific investigator, affordable investments can now yield "keep-up" performance for SARs, and on-board processors are becoming a part of the planning horizon for future space-based systems.

c. Hybrid Systems

For the future, SAR processing technology will come full circle. While digital processors were supplanting the traditional optical processors in the 80s and 90s, optical technologies have begun a revolution of their own. Important breakthroughs in acousto-optic and piezoelectric modulators, and very large format image collection planes make it possible to consider designs using the benefits of compact, power efficient, fast optical computers. Such advances will help create new ground-based and improved on-board SAR processors, well suited to the demands of operational applications. Digital technologies will persist and implementations can be configured into affordable hybrid systems incorporating the best in digital and optical technologies. Considering the continuing improvements of both the digital and optical technologies, it is not unreasonable to expect that a high performance on-board SAR processor, capable of providing a direct-downlink compressed data stream to operational users, will become a reality within the next decade. Software will also evolve to portable, application-specific, codes capable of largely unsupervised automatic-target-recognition, and geophysical classifications to support a wide range of environmental and military applications.

5—Space-Based SAR Data Access

a. Alaska SAR Facility

Access to space-based SAR data in support of operational applications has been, and continues to be, very limited. In 1985, NASA and the Jet Propulsion Laboratory (JPL) began the design and implementation of the Alaska SAR Facility (ASF), located at the University of Alaska in Fairbanks, Alaska. The ASF was designed to collect, process and archive SAR data from the ERS-1 and JERS-1 satellites in support of Arctic regions science, with a heavy emphasis on sea ice research. The ASF design was such as to primarily support non-real time SAR processing to support science investigations, although provisions were made to process a limited amount of quick-look data for both science and applications purposes. Today, the ERS-1, ERS-2, and RADARSAT SAR data are being collected during each satellite pass through the ASF station mask using a direct downlink. JERS-1 data are also collected during each pass over the ASF, with the further provision to collect and process the tape recorded data during pre-selected passes. The ASF has been operational since the launch of the ERS-1 satellite in July 1991, and continues to provide processed SAR data to the user community.

b. National Ice Center

The Navy-NOAA-Coast Guard National Ice Center (NIC) in Suitland, MD was the first operational center to utilize ERS-1 and JERS-1 data to support operations. The NIC initially accessed these SAR data at the ASF, using a specially designed SAR communications system to store and forward, in near-real time, quick-look SAR image data over a time-shared satellite communications circuit. This system served the NIC through its SAR demonstration phase. A more simplified arrangement using Internet is now in place to support operations, although policy considerations limit the amount of quick-look data delivered to the NIC in near-real time. Beginning in the 1991 time period, two additional pathways were established to provide data to the NIC. One 56 kbps circuit now exists between the NIC and the Ice Centre Environment Canada (ICEC) to permit the exchange of SAR image data between the two centers from the ASF and the Canadian station in Gatineau. Other operational ice products are also exchanged over this circuit. An additional pathway also now exists to provide access to ERS-1 and ERS-2 SAR data collected and processed by the Norwegian satellite station in Tromso, Norway. A combination of satellite communication and Internet circuits is being used to provide these SAR data to the NIC in near-real time. Figure 5-1 illustrates the geographic coverage provided by the three stations, plus the Canadian Prince Albert Station, with near-real time SAR processing and delivery capabilities. For operational users of ERS-1, ERS-2, and JERS-1 SAR data not requiring access in near-real time (1-6 hours), SAR image data are available from the archives at the ASF, from the Canadian Centre for Remote Sensing (CCRS) for data collected and processed at the Canadian stations in Prince Albert and Gatineau, and from the European Space Agency for data collected and processed at European and other foreign ground stations.

While the pathways for near-real-time access to ERS-1, ERS-2 and JERS-1 SAR image data are presently more or less sufficient to support the needs of the NIC, they are inadequate for multi-user access to RADARSAT data. Preliminary estimates of operational user requirements (U.S. Government only), which do not even reflect all the potential users of RADARSAT data, indicate that the data volumes required will far exceed the capacity of the present communication pathways. As a result, plans are underway within NASA, NOAA and Navy to upgrade the present SAR processing capabilities at the ASF,

and delivery capabilities at the ASF, Gatineau, and the Tromso ground stations. Significantly improved SAR processing capabilities should be achieved at all three stations, primarily to provide for increased volumes of RADARSAT data in the "SCANSAR" mode, in near-real time.

c. Access to RADARSAT

While the ASF, Gatineau and the Tromso stations provide satisfactory RADARSAT coverage of Arctic regions, Canada, the northern United States, and Northern Europe, additional ground stations in the central U.S. and foreign countries will be needed to obtain global coverage with the RADARSAT SAR. The spacecraft is equipped with two tape recorders, each capable of storing 14 minutes of data per orbit. However, to preserve the life of these recorders, the Canadian Space Agency (CSA) is expected to exercise considerable restraint on their use (a planned maximum of 5 record events will be made before rewind and playback)—hence, the tape recorders cannot be fully relied upon to obtain global access to near-real-time SAR imagery. Although the tape recorders will be used sparingly, they will be available for limited support to operational applications. Also, early in the RADARSAT mission, the tape recorders will be devoted to the Antarctic mapping task, a high priority for NASA. Provisions have also been made to use the tape recorders in support of extraordinary operations, including environmental emergencies, national security threats, and law enforcement missions. To respond to this challenge, RADARSAT International (RSI) has established contractual arrangements with several foreign ground stations to collect RADARSAT data. These arrangements provide for the collection and storage (on tape) of RADARSAT data, with the tapes to be forwarded to the Gatineau station for subsequent image processing and archiving. Few foreign ground stations will, under the RSI arrangements, have a near-real-time processing capability. And few, if any, will have a near-real-time user delivery capability. A notable exception will be the Tromso, Norway station where a 14-minute turnaround capability already exists for ERS-1 and 2 SAR processing. RSI is currently negotiating with the following countries to establish RADARSAT collection capabilities at existing ground stations:

- Norway (Tromso)*
- Singapore**
- Japan (Hatoyama)**
- United Kingdom (West Freugh)**
- Taiwan**
- Brazil**
- Australia

* Will have a near-real-time processing and delivery capability.

** May have a near-real-time processing capability.

RSI also expects to enter negotiations with the following stations within 1-2 years:

- South Africa
- Israel

A limited amount of RADARSAT data will be provided to the U.S. Government at no cost in return for NASA's provision of launch services for RADARSAT. Lockheed-Martin Corporation has purchased from the Canadian Government the exclusive marketing rights for sale of data to U.S. Government agencies. This means that if U.S. Government agencies desire to obtain RADARSAT data in excess of the limited amount of free data, they must purchase the data from Lockheed Martin which will coordinate with RSI to integrate these orders into their processing of other customer orders.

d. Transportable Stations

As a consequence of these limitations, some potential operational users of RADARSAT data are considering the use of transportable ground stations for the collection and processing of RADARSAT data. Such stations, patterned after High Resolution Picture Transmission (HRPT) stations for the NOAA polar-orbiting satellites, and possibly compatible with the U.S. military's new Eagle Vision Landsat/Spot mobile receiving stations, would be located in geographic locations of operational interest to users. Such ground stations could support an on-site analysis capability and/or an additional communication capability for the fast delivery of processed image data to operational centers. Germany has developed a transportable system for ERS-1 and ERS-2, now located in the Antarctic, and private-sector initiatives in the U.S. and Canada are underway to develop transportable ground stations for RADARSAT. Of course, any implementation of mobile ground stations and data acquisition/processing of RADARSAT imagery must be coordinated with RSI and/or Lockheed-Martin, as appropriate.

e. NOAA Satellite Ocean Remote Sensing

NOAA, under its NOAA Satellite Ocean Remote Sensing Program (NSORS) initiative, is making investments to establish a SAR data access, archive, and distribution capability for both operational and research users. The centerpiece of this capability is a Satellite Active Archive (SAA), residing on several RS6000 UNIX workstations located at the NOAA/NESDIS facilities in Suitland, Maryland. The SAA provides user access to satellite data via a catalog and browse facility with both character and graphical interfaces (a Mosaic interface is under development). Data can be searched by geographic area, time, sensor, and platform. Browse imagery is available, and data can be ordered for electronic delivery or delivery via mailed media. Currently, the SAA contains NOAA polar-orbiting and geostationary satellite imagery. Data to be added soon are NOAA atmospheric sounder data, microwave imager and sounder data, and derived products. NOAA is planning to add SAR imagery from RADARSAT and ERS-2 to the SAA during 1996. These images will be stored in a lossless compressed form for browsing and downloading by authorized users. For RADARSAT, U.S. Government agencies will be authorized access. ESA investigators will also be authorized access to ERS-2 data.

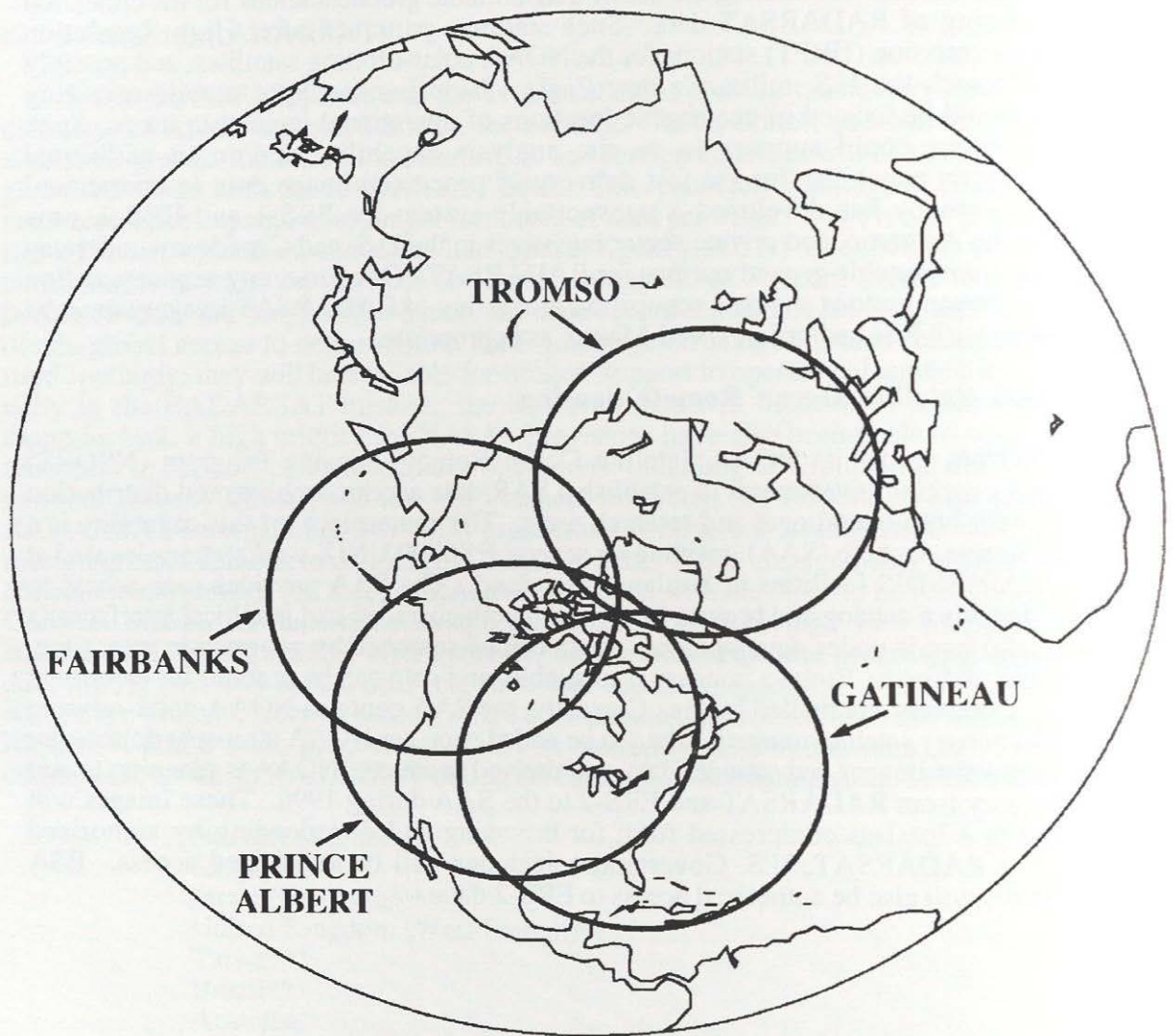


Figure 5-1. Polar projection of the Northern Hemisphere with Tromso, Gatineau, Fairbanks and Prince Albert ground stations.

6—Data Costs

a. European Policy

The European Space Agency (ESA) has established a pricing policy for all ERS-1 and ERS-2 SAR data. Under special arrangements for support to scientific investigations and demonstration projects, ERS-1 SAR data have been provided to selected users at no cost. Under agreements between the U.S. Government and ESA and NASDA, ERS-1, ERS-2 and JERS-1 data collected and processed at the ASF are currently made available to U.S. government users at either no cost, or for the cost of reproducing products. ERS-1, ERS-2 and JERS-1 data collected and processed at other stations must be purchased by U.S. users in accordance with ESA and NASDA policies, respectively. As an example, under a special arrangement, the National Ice Center purchases a very limited amount of ERS-1 SAR data from the Tromso Satellite Station for amounts ranging from \$600 to \$900 (U.S.) per 100-km x 100-km image, depending upon the spatial resolution to which the image is processed. The limits on the amount of data purchased are primarily imposed by cost/budget considerations.

b. RADARSAT Policy

RSI is a private-sector company under contract to the CSA to process, distribute, and market RADARSAT data to the user community. This creates a quasi-commercial operation for RADARSAT through which some of the costs of developing and operating this spacecraft are recouped through data sales. Thus, RADARSAT is placed on a similar footing to the U.S. Landsat program, for which data sales are handled commercially by the EOSAT Corporation.

RSI has established an access policy for all RADARSAT data collected by foreign ground stations. This policy is based upon the observation time (data take) of the SAR. Under an agreement between NASA and CSA, a defined amount of data will be provided to U.S. Government agency users at no cost. The amount of no-cost data is defined by a formula which takes into account the cost of the U.S. launch of the RADARSAT satellite. The apportionment of this U.S. "allocation" is currently the subject of NASA-NOAA negotiations. NASA is anticipated to receive a substantial portion of the U.S. allocation in return for providing the RADARSAT launch vehicle.

A RADARSAT price list has recently been issued by RSI. Prices quoted are on a "per scene" basis, with additional premiums charged for special processing or fast turnaround imagery. Scene sizes are determined by the mode and look angle requested by the customer. The cost per image, therefore, will be a function of both the SAR mode under which the data are obtained, the level of processing, and the delivery time. Reaction to the pricing policy by potential operational users remains to be seen. However, discussion among the Interagency Working Group members seems to indicate that two issues may arise:

- The RSI "one price list fits all" policy may not be optimized to the situation in which there are very different kinds of users. For instance, a mapping customer may purchase and study a RADARSAT image extensively and he/she will expect to derive lasting value from the image. On the other hand, an ocean scientist or operational ice or weather monitoring customer may require SAR imagery in near-real time to quickly extract information on environmental conditions. He/she will derive short term value from the image and the value of

the information, and of the image itself, is highly perishable. These two customers may have very different expectations regarding the price they are willing to pay for SAR imagery and, therefore, flexibility in contracting arrangements may be essential.

- Also, U.S. Government funding for operational space systems has historically been provided to the agencies that acquire, launch and operate the systems (e.g., NASA, NOAA, and the Space Systems Commands in DOD). Users generally have had only to pay for their unique data processing and applications requirements, with data provided "free." The model for this is, of course, weather data from NOAA and Air Force satellites. Although purchase of data from commercial remote sensing systems, such as RADARSAT, may prove to be less expensive to the government than building and operating an organic government spacecraft, the migration of funding from traditional space agencies to user agencies, which would have to happen in order to enable large scale data purchases, would look (to budget analysts) like a "plus up" requirement for these users. And, as a result, large data purchases are not likely to be funded in the current fiscal environment.

These issues would appear to create significant obstacles to the creation of a viable market for operational use of RADARSAT data in the U.S. It has already been seen that the quasi-commercial operation of Landsat 4 and 5, in which government agencies must purchase, from a private company, imagery collected from a taxpayer-purchased spacecraft, severely limits data sales. It is widely believed that this has resulted in government utilization of Thematic Mapper imagery which falls far below its potential, given the clear value of this very powerful imagery information source in any number of operational government applications.

7—Operational Applications Development

To capitalize on the promising results of past SAR research and to offset the effect of the negative factors regarding the prospects for commercial data purchase, it is very clear that the value of SAR in operational applications must be demonstrated. Operational demonstrations need to be done, not by the research community that has already proven the potential of SAR and which is motivated primarily by the continuation of research funding, but by those agencies which would actually use the measurements and products that SAR would provide. Only then will operational requirements be written and validated and funding decisions made regarding the purchase of data by user agencies.

a. Need for Demonstration Projects

SAR image data are a relatively new data type requiring special interpretation techniques in order for users to utilize the data in most operational applications. In addition, most operational users require a period of experimentation and demonstration with SAR data in order to test the utility of SAR in their applications—all this, prior to fully using space-based SAR to support operations. Unlike Canada, where the RADARSAT Program is spawning Canadian Government investments in SAR applications development, not enough is being done in the U.S. to foster the training of SAR users and to sponsor the conduct of operational demonstration projects which can validate the operational utility of SAR and provide the learning bridge to the use of space-based SAR on an operational basis. SAR research initiatives with such organizations as NASA, the Office of Naval Research (ONR), the Department of Energy (DOE) and the National Science Foundation (NSF) make little or no provision to transition SAR research results to operations, thus further hindering the ability of operational users to use the latest technology advances in support of operations.

There are, however, some modest exceptions. NOAA, under its NSORS Program is sponsoring SAR research and demonstration projects in coastal ocean, wetlands, hydrology, and sea ice applications, including research to develop multi-sensor data fusion methods and automatic feature detection techniques. Also, the Oceanographer of the Navy sponsored a demonstration project leading to the first operational use of space-based SAR at the NIC. And the Naval Research Laboratory (NRL) continues SAR research for Navy applications in littoral regions, including system upgrades at the NIC to utilize RADARSAT data. NRL also has cooperative projects with Norwegian and British partners to develop SAR algorithms for shallow water applications and surface ship and ship wake detection. The U.S. Coast Guard is sponsoring demonstrations to evaluate the effectiveness of SAR to detect and track oil spills and to identify icebergs which are hazards to navigation.

b. New Investments Required

The full potential of space-based SAR in agency operational applications will not be realized until substantial investments are made in demonstration projects using both aircraft and space-based SAR platforms, and performed in an operational setting, which assess the cost-effective utility of the data to each agency's mission. Companion investments must also be made in advanced research initiatives, where incentives are provided to transition SAR research results to operations, an expensive and time consuming process. A more effective means must be sought to facilitate the interaction between SAR researchers and operational users so that operational requirements are made known to the research community, while promising and mature SAR research results are described to users with operational applications. With the launch of RADARSAT, there are four civilian SAR

satellites on-orbit, and more are approved or planned during the next decade. There will be a continuity of SAR data in the foreseeable future and, therefore, the opportunities to exploit space-based SAR to support operations are compelling.

8—Future Initiatives and Opportunities

a. SAR-2000

Acting upon the assessments and recommendations provided by the science community and documented in a report submitted to the Committee on Earth Sciences of the Space Sciences Board of the National Research Council entitled "Spaceborne Synthetic Aperture Radar: Current Status and Future Directions," NASA has constructed a major SAR program plan named "SAR-2000, Spaceborne Imaging Radars for Earth Observations." This program plan is shaped by the science community conclusions that active microwave sensors will become increasingly important in the future and, while playing a secondary role to electro-optical sensing systems today, will likely reverse that role in the future. The report also observes that one of the most compelling uses of SAR for solid Earth studies involves interferometric SAR (IFSAR), citing the ability of IFSAR data to permit the construction of a global digital elevation model, to detect surface deformation at the millimeter level associated with natural hazards such as earthquakes and volcanic eruptions, to measure coastal ocean currents, and to measure the velocity and topography of glaciers and ice sheets. The NASA SAR-2000 Plan incorporates IFSAR as a performance centerpiece, but also incorporates multiparameter SAR systems to acquire data on such important environmental parameters as vegetation biomass estimates and classification, the detection of flooding and flooding under vegetation, measurement of snow pack depth, and detecting ocean surface slicks and distinguishing between oil spills and natural surfactants. The NASA SAR-2000 characteristics emphasize small, focused, affordable missions conducted within a coordinated international SAR program, the utilization of high technology, and lightweight SARs which capitalize upon advancements in NASA's New Millennium Program.¹ This initiative provides an expansion of a core radar technology component, provides for an aggressive data exploitation and outreach program, and provides for a long-term series of vital scientific measurements.

How this program affords opportunities for users to acquire and utilize data to support operations remains to be defined, and presents a challenge to the operational SAR community to shape this and companion programs to meet both scientific and operational needs.

The concepts of a coordinated international SAR program in the early 2000s is being pursued by NASA, and, at an April 1995 Space Studies Board meeting, discussions between representatives from the U.S., Canada, Japan, ESA, Italy, and Germany, were held to explore the concept of an international SAR constellation. This international concept grows out of a realization that within the next decade, no one country is likely to afford to undertake the exploitation of the emerging scientific and operational potential of space-based SAR, given the declining space agency budgets worldwide. Cooperative partnerships are now viewed as essential to pursuing a robust space-based civilian SAR program. The envisioned concept of an international SAR constellation would be comprised of multiple small satellites, developed, funded, and operated by different world agencies, with each satellite providing SAR measurements at generally one frequency. The satellites would fly in formation to enable interferometric and multiparameter applications of SAR data, allow the pursuit of high priority objectives including high- and variable-

¹ New Millennium is a NASA initiative to enable frequent, affordable space missions in the 21st century by identifying, developing and flight-validating key spacecraft, instrument and operations technologies which can significantly contribute to lowering life cycle costs of missions.

resolution global mapping, observations for hazard monitoring and mitigation, coastal ocean feature measurements, and studies/applications supporting ecology, hydrology, and geology. An enormous amount of work remains in order to design the political, economic, commercial, and technical dimensions of such international SAR partnerships. However, the concept appears to have considerable merit, and the operational SAR community must be actively involved in the discussion and planning process to ensure that the emerging concepts embrace operational requirements and considerations. It is unlikely that U.S. resources will be adequate to permit separate scientific and operationally-oriented civilian SAR satellite systems anytime in the foreseeable future.

b. A Third Space Radar Laboratory (SRL-3) Mission

Based upon the successes of the 1994 SIR-C/X-SAR SRL-1 and SRL-2 missions, and the desire to increase the momentum of the U.S. civilian space-based SAR program, serious consideration is being given to flying an SRL-3 mission in the 1997 time frame. Strong recommendations by both science and operational users to use SAR interferometry to conduct global topographic mapping have driven the objectives for an SRL-3 flight, possibly serving as a precursor to a dedicated topography SAR (tentatively being called the Global Topography Mission or GTM) in the 2000 to 2002 time period. The SRL-3 mission would encompass a Shuttle Radar Topography Mapper (SRTM) (Figure 8-1), devoted to performing a medium resolution topography mission from the Shuttle. An 11-day mission, which could be launched in the 1999-2000 time frame, would acquire quasi-global topography (coverage from 60 degrees North to 60 degrees South latitude) with 30-m spatial resolution and 9- to 12-m vertical accuracy (DTED-2 level). The SAR sensor would be a SIR-C/X-SAR, augmented with a C-band receive-only antenna attached to a 62-m boom for topographic mapping. Additional features would include an 8-m receiving SCANSAR C-band antenna, a metrology system for baseline orientation/length determination, and the provision of a ground SAR processor to permit all data to be processed into map products by one year following the completion of the mission.

While the IFSAR topography component of the mission would occupy a considerable portion of the mission timeline, NASA could provide opportunities to obtain SAR data in support of demonstration projects designed to evaluate the utility of the multiparameter, interferometric SAR in a variety of operational applications. In anticipation of the possibility of this SRL-3 mission, several agencies have begun to define candidate demonstration projects so that current mission activities and resource allocations can be tailored to support a selected set of demonstrations.

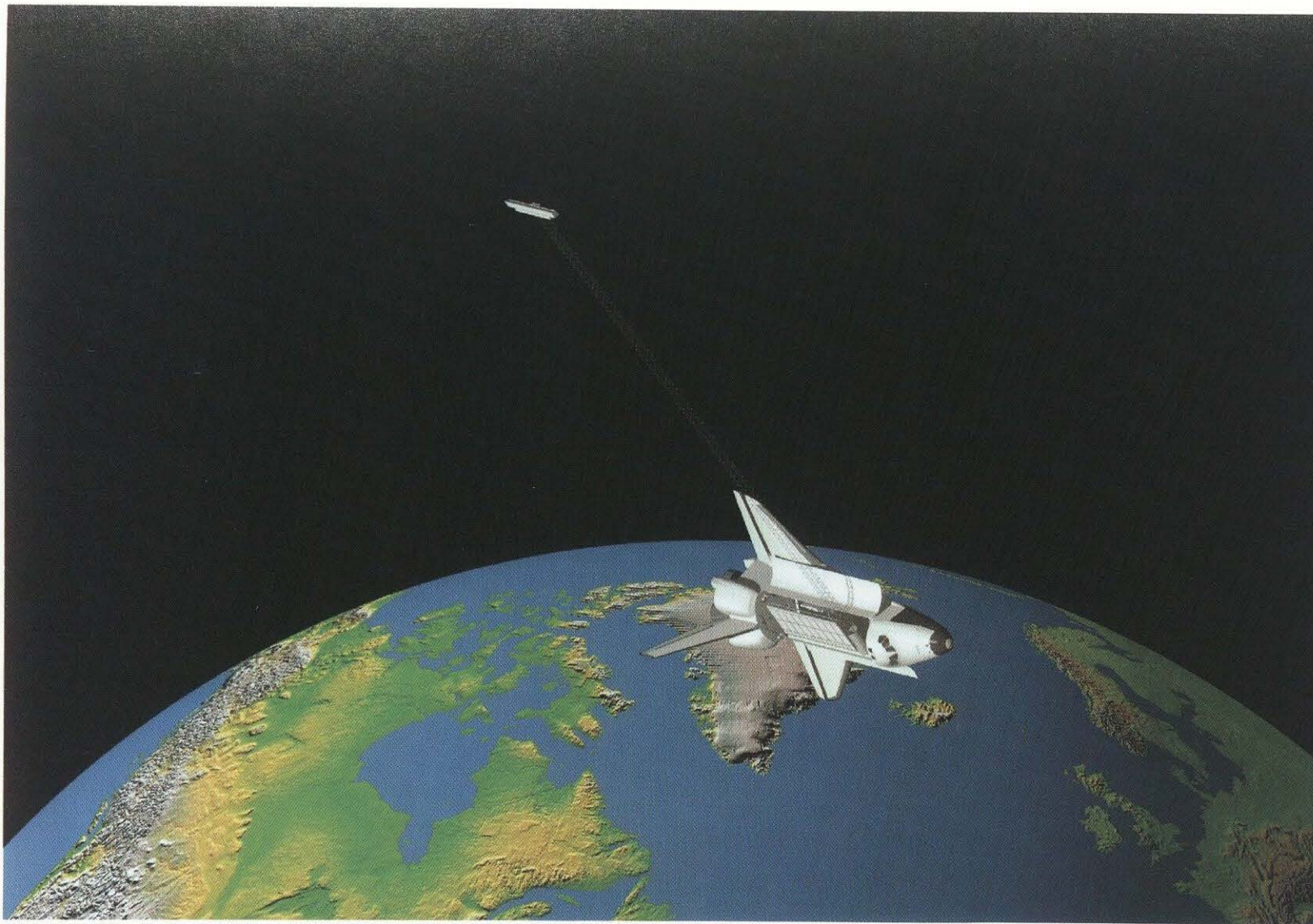


Figure 8-1. SRTM, a joint project of NASA, DMA, and the German and Italian space agencies, will map the world in three dimensions. Using the SIR-C/X-SAR hardware, SRTM will produce, in a single 11-day Shuttle flight, data sufficient to produce a rectified terrain-corrected C-band mosaic of 80% of the Earth land surface at 30-meter resolution.

9—SAR Requirements to Support Operations

a. Operational Categories

The operational applications of space-based SAR often require a sensor performance not unlike that needed to conduct scientific investigations of the environment. While science requirements are frequently categorized by the science discipline (geology, hydrology, oceanography, etc.), those for operational users are best grouped by the application. For this report, the selection of categories of operational applications has been influenced by the efforts of the Central Imaging Office in their development of the Community Imagery Needs Forecast (CINF). This CINF has resulted in an extensive database of remotely-sensed imagery requirements, including those of civil, military, and intelligence users. An element of the CINF is a segment delineating the civil and environmental needs, including those for SAR. So that there can be a close correlation with the CINF database, the operational SAR “desirements” outlined in this report are divided as follows:

- Mapping And Charting
- Resource Monitoring and Management
- Pollution And Waste Threats
- Natural Hazards
- Oceans And Ice
- Enforcement And Surveillance.

b. Assessment Limitations

The potential requirements and applications described on the following pages have been drawn from material supplied by agency representatives participating in the Interagency Ad Hoc Working Group on SAR. They are preliminary in nature and not exhaustive. The requirements will be refined through additional interaction with agency representatives and review of the CINF database. SAR is a relatively new data type for many operational users. Consequently, it is not always clear to the new user, where SAR can find utility in their applications. While an education process is underway, and new SAR satellites are providing more data each day for new user experimentation and familiarization, the fact remains that operational applications of SAR are still limited and will be continually emerging as user knowledge increases. This report can only reflect a snapshot of requirements as the user community understands them at this point in time.

c. Data Blending

Many of the SAR applications and requirements described in this report are based on the use of SAR data to augment other remotely-sensed data, particularly multispectral optical data such as are provided by the Landsat and SPOT satellites, which are data types familiar to many operational users. Multiparameter SAR data offers the potential to provide unique observational signatures when blended with multispectral information (Figure 9-1).

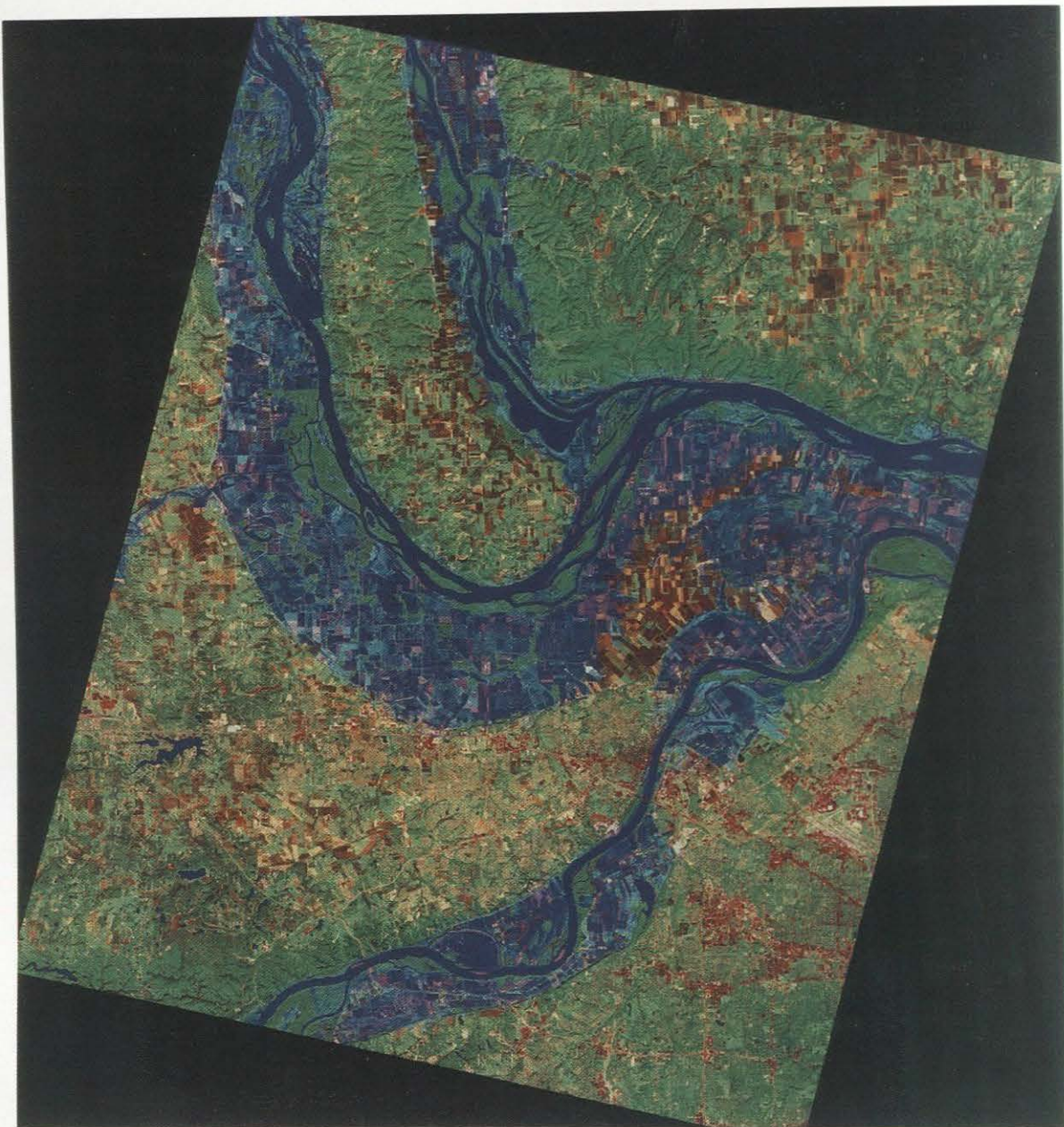


Figure 9-1. A merged SPOT multispectral image and an ERS-1 SAR image of the 1993 Mississippi River flood. The 1988 SPOT image provides information about the pre-flooded river course (dark blue) and surrounding land use. Flood limits extracted from the SAR image are represented on the scene as purple-blue areas. These images illustrate the data analysis benefits provided by data blending. (ERS-1 SAR image provided courtesy of RADARSAT International Inc. ©ESA SPOT satellite image provided courtesy of SPOT IMAGE Corporation. ©CNES Color image processed by ITD Space Remote Sensing Center, Stennis Space Center, Mississippi).

10—Applications

The following applications were provided by the working group members as examples of real-world operational missions being conducted by their agencies and for which SAR data may be effective, given the availability of data with the appropriate attributes, processing capacity, applications algorithms, and a supporting infrastructure.

10.1 Mapping And Charting

a. Definition

Mapping and charting pertains to the topographic and geographic feature mapping of land surfaces, and the charting of coastlines and the topography of the seabed, including obstacles, shoals, and other hazards to navigation.

b. Mapping

Space-based SAR, configured for interferometric measurements, provides a unique capability to acquire high accuracy (DTED-3 level) topographic data in a rapid, cost-effective fashion. The all-weather capability of SAR permits the acquisition of topographic measurements in cloud-covered regions and areas of denied access. SAR-derived topographic data (Figure 10-1) can augment existing topographic mapping data to yield DTED-3 level maps on a global basis.

Within the Department of Interior, the Bureau of Indian Affairs can utilize topographic and boundary maps of reservation areas, while the Bureau of Land Management has need for image-derived maps of selected regions of the U.S. The U.S. Geological Survey has broad requirements for topographic and geologic feature maps of the U.S. and selected foreign regions, particularly cloud-covered equatorial regions. The Defense Mapping Agency (DMA) has extensive need for worldwide image-derived digital terrain elevation data and hydrographic charts to support production of MC&G data for a wide range of military applications, including navigation, targeting, mission planning and rehearsal, modeling and simulations, tactical operations, and intelligence gathering. Here, too, the area of interest for SAR-derived data are the traditionally cloud covered areas within ± 15 degrees of the equator, as well as foreign regions of denied access. The Army Corps of Engineers, at the Topographic Engineering Center share many of the DMA requirements for mapping (terrain contours, classification, and feature extraction) with need for the use of interferometric SAR (IFSAR) techniques to conduct rapid mapping for a range of military applications, including targeting, support to combat operations, and mission planning, and the creation of synthetic environments to aid in training, concept development, mission rehearsals, and performance evaluations. The Drug Enforcement Administration (DEA) requires accurate topographic/terrain maps to aid in raid planning (Figure 10-2) and to support other operations, especially in cloud-covered regions such as Peru. Because these operations are most often conducted in foreign areas where access is either denied or otherwise to be avoided, space-based SAR data collection provides a unique capability for mapping purposes. The U.S. Air Force intelligence community requires IFSAR-derived image data to generate terrain battle maps and scene battle maps for use in the next generation weapons guidance systems. The IFSAR-derived maps, developed in both peacetime and during crisis periods, will provide a map-matching guidance capability to augment data from a Doppler radar altimeter and processed using advanced navigation algorithms, to provide a highly accurate weapons delivery capability. The Navy and Marine Corps have both mapping and charting requirements which support

operations in the littoral battle space, including the planning and execution of amphibious landings (Figure 10-3), mine sweeping operations (Figure 10-4), and the insertion/recovery of special warfare teams (Figure 10-5). Maps of the coastal shoreline are required to define the shape and dimensions of the beach, exits, resupply points, landmarks, and obstructions. For the hinterland, topographic maps are needed to identify lines of communication, landmarks, and trafficability conditions (Figure 10-6).

c. Charting

NOAA requires data for charts to identify hazards to navigation, including shoaling conditions, reefs, and obstructions in the U.S. near-shore regions, while the USCG has an active interest in the correct positioning of navigation hazards in ocean areas.

10.2. Resource Monitoring and Management

a. Definition

Resource monitoring and management covers a broad range of applications, including mineral surveys, snow cover measurements, crop identification and assessments, wetlands monitoring, regrowth surveys of forest lands, and fish stock assessments and management. Some application-specific resource/land cover mapping requirements are included in this category.

b. Multispectral Use

Many agencies have, for several years, been supporting operational resource monitoring and management activities with remotely-sensed multispectral data, such as are obtained from Landsat and SPOT satellites. It is expected that space-based SAR data (particularly from multifrequency, multipolarization SAR sensors) will permit the extraction of unique surface signature measurements, including soil moisture (Figure 10-7), and the ability to penetrate forest canopies to detect surface water (Figure 10-8), thus augmenting the multispectral data to yield significantly enhanced information on environmental parameters. In addition, SAR will provide observational data not generally available in the cloud-covered polar and equatorial regions.

c. Fire Fuels

Requirements for fire fuels maps are shared by several agencies, including the Bureau of Indian Affairs (BIA), the Bureau of Land Management (BLM), and the National Park Service (NPS) of the Department of Interior, and the U.S. Forest Service (USFS) of the U.S. Department of Agriculture (USDA). SAR-derived vegetation classification maps (Figure 10-9) may aid in meeting these needs.

d. Vegetation and Land Cover

Vegetation and land-cover maps (Figure 10-10) are important resource management tools for a number of agency users which include the BLM, the Bureau of Reclamation with an emphasis on the extent of irrigated agricultural land in the Western U.S., the NPS, the U.S. Fish and Wildlife Service (USF&WS) and the BIA with their needs in wildlife habitat assessments and land-use patterns affecting fish and wildlife resources, the National Biological Survey (NBS) with a focus on biological resource analysis, and the U.S. Geological Survey's (USGS) interest in the often cloud-covered Alaska region.

e. Crop Identification

Crop identification (Figure 10-11), inventory and assessment requirements exist for several services of the USDA, including the Foreign Agriculture Service and the National Agricultural Statistical Service.

f. Forest Condition Assessment

Both the USGS and the USFS share requirements for forest condition assessments, including the mapping of deforestation and deforestation rates (Figure 10-12).

g. Land Inventories

The BIA requires maps to develop inventories of agricultural lands on reservations. Both the USF&WS and NOAA have requirements pertaining to wetlands, and the monitoring of their condition, flooding status (Figure 10-13), and ecology.

h. Mineral Resource Assessments

The USGS and BLM need data to support mineral resource assessments, including the identification of mineralized zones and rock alteration areas, while the Bureau of Mines requires land observations for the inventory and characterization of abandoned mine lands.

i. Sea Ice and Snow Maps

The Minerals Management Service (MMS) has requirements for SAR-derived seasonal sea ice measurements of ice extent, type and motion of Arctic ice (Figure 10-14) in support of outer continental shelf oil and gas lease allocations, and, along with NOAA, determining how sea ice affects the migration of marine mammals. NOAA also requires measurements of snow cover (Figure 10-15) to determine snow water equivalence to support water supply forecasting and hydroelectric power management.

j. Coastal Wetlands

The NOAA National Marine Fisheries Service (NMFS) will find utility in blended Landsat TM and SAR-derived measurements of the land-water interface in coastal wetlands, where the length and convolution of the interface is directly related to the shrimp production and shrimp recruitment estimates for the coastal zone. NMFS may also benefit from SAR-derived observations of surface roughness changes due to freshwater lenses in open saltwater areas resulting from freshwater diversion projects which pump freshwater through wetland marshes, thus affecting salinity conditions which impact oysters, shrimp, and small pelagic species in local fisheries.

10.3. Pollution and Waste Threats

a. Definition

This category pertains to applications involving pollution and waste threats to the environment, including waste site monitoring, ocean, lake, stream, sea ice, and land pollution detection and mitigation, and oil spill detection and tracking.

In addition to the day/night capabilities of SAR and its ability to make observations in the cloud-covered polar and equatorial regions, the multipolarization SAR configurations

permit the determination of unique signatures associated with some pollutants, especially when fused with multispectral data from such sensors as on the Landsat and SPOT satellites.

b. Runoff Patterns

The USGS and NOAA, in support of the National Water Quality Assessment program, may utilize SAR data to aid in the characterization of land surfaces to define runoff patterns and soil types.

c. Ocean Transport

SAR-derived measurements of ocean circulation patterns (Figure 10-16), surface winds, and wave spectra can be utilized by NOAA/NMFS to assess the transport of pollutants (Figure 10-17) in the coastal regions and estuaries which threaten juvenile nurseries and adult fish stocks.

d. Oil Spills

NOAA can utilize SAR-derived ocean circulation signatures, surface winds, and wave spectra to aid in the track prediction and disbursement of oil from spills. Wide-area SAR observations of ocean regions can also be utilized by the USCG, the Naval Oceanographic Office (NAVOCEANO), and the Office of Naval Intelligence (ONI) to detect and monitor oil spills (Figure 10-18), and to differentiate between manmade and natural surfactants.

The DEA may be able to utilize the SAR-derived detection of surface slicks on rivers, streams, and estuaries to identify nearby clandestine drug manufacturing sites where chemical dumping occurs into these waterways

10.4. Natural Hazards

a. Definition

The category of Natural Hazards pertains to events which pose hazards to, and threaten life and property, and include such events as earthquakes, volcanic eruptions, floods and forest fires.

b. Volcanic Eruptions and Earthquakes

The USGS has requirements to monitor and predict volcanic eruptions, and IFSAR change-detection techniques could be used to measure surface displacements as prediction indicators of volcanic eruptions (Figure 10-19). Similar techniques can contribute to the USGS requirements to track mud and lava flows as well as ash deposits (Figure 10-20) which pose hazards to local populations following volcanic eruptions. Multiple-pass SAR observations of populated areas following earthquakes (Figures 10-21, 10-22) and volcanic eruptions can support USGS and National Biological Survey (NBS) requirements for damage and impact assessment maps (Figure 10-23); these SAR observations are also available to support the disaster relief efforts of the Federal Emergency Management Agency (FEMA).

c. Hurricanes

Similar SAR imagery can yield damage assessment data following hurricane and tropical storms for use by FEMA. Blended SAR and multi-spectral visible imagery can produce data from which USGS can generate flood plain assessments.

d. Flooding

For USGS, FEMA and NOAA, blending the same imagery from observations of flooded regions can measure the extent of flooding (Figure 10-24), monitor flood water levels, determine standing water beneath canopies, and assist in the assessment of the damage to crops, local populations and industries.

e. Mines

The Bureau of Mines within DOI has requirements to identify the subsidence potential of abandoned coal mines, and IFSAR change-detection measurements of the surface structure may aid in defining these potential hazard zones.

f. Forest Fires

SAR observations of forest fires, combined with surface wind and humidity data, can aid the USFS in defining tactical strategies for fire fighting. Post-fire SAR measurements (Figure 10-25) may aid in assessing the extent of damage, the potential for flooding, mud flow and landslides, and support in reforestation planning.

10.5. Oceans, Great Lakes and Ice

a. Definition

Oceans and Ice, as a category, pertains to applications involving oceanography, sea and lake ice, icebergs, and glaciers. A number of applications involving the measurement of ocean and ice signatures are described in other application categories because the SAR-derived ocean/ice signatures support a more specific operational application. An effort has been made to eliminate overlap or duplication across categories.

b. Ice Operations

The Navy, NOAA, and the USCG, as operators of the National Ice Center (NIC), have requirements to provide support to icebreaker operations in polar regions (Figure 10-26) and the Great Lakes (Figure 10-27), to re-supply activities in Arctic and Antarctic regions and to military operations in ice infested waters. All-weather SAR observations of sea ice characteristics and dynamics (Figure 10-28), open water and polynyas, can aid in the preparation of route maps in ice-covered areas to support these NIC navigation support activities. SAR observations of site-specific military operations can aid in site selection, aircraft landing area determinations, and hovercraft ingress/egress routes. The NIC also requires SAR-derived observations of the ice edge and ice motion in the marginal ice zone (MIZ) to aid in ambient noise level determinations for Antisubmarine Warfare (ASW) operations. SAR measurements of leads, and the location of open water and thin, first-year ice will aid the NIC in support to submarine safety (Figure 10-29) in Arctic regions. NOAA can utilize SAR-derived observations of ice conditions in the Great Lakes to support commercial shipping and icebreaker operations during the winter season. The USCG International Ice Patrol has requirements to detect and track icebergs (Figure 10-30) in the

Baffin Bay and North Atlantic regions which pose a hazard to shipping. Space-based SAR, in conjunction to aircraft SLAR observations, may contribute to this iceberg detection and tracking capability, and provide input to iceberg maps and the determination of the southern limits of all known iceberg notices, routinely sent to all ships at sea.

c. Littoral Warfare

The Naval Oceanographic Office (NAVOCEANO), in support of shallow water ASW, can utilize SAR-derived surface winds, wave spectra, and ice motion in the MIZ to aid in determining ambient noise levels to support acoustic performance predictions. The NAVOCEANO, in support of the planning and execution of amphibious landing operations, mine countermeasure operations, and special warfare missions, can assimilate SAR-derived measurements of ocean currents (using IFSAR techniques), coastal ocean feature signatures, including frontal boundaries (Figure 10-31), eddies, and shoaling and refraction patterns indicative of topographic features and gradients of the seabed (Figure 10-32), to initialize regional numerical littoral models. SAR-derived wave spectra and surface wind velocities can contribute to the determination of coastal wave heights and surf conditions.

d. Search and Rescue

The USCG, in its search and rescue operations, can utilize IFSAR-derived ocean current measurements and SAR-derived surface winds and wave spectra as input to a drift model to improve predictions of target tracks and locations, and increase chances of timely rescue.

e. NOAA CoastWatch

NOAA can also benefit from SAR measurements of coastal ocean features to support the CoastWatch Program, to aid in understanding the dynamics of beach erosion and sediment transport, and, for fisheries management applications, the dynamics associated with nutrient concentration, upwelling conditions, and coastal ocean conditions optimum for release of hatchery-raised salmon smolts. Further, to aid in fisheries management, NOAA/NMFS needs IFSAR-derived coastal currents for monitoring the strength of on-shore transport of eggs and larvae of estuarine-dependent species (constitutes 90% of the commercial fisheries in the Gulf of Mexico), as well as estimates concerning the source and trajectory of fish and endangered species mortalities (e.g., dolphins, whales, sea turtles) to determine their origin and cause of mortality. Ocean features are known to affect the distribution and abundance of many marine species, hence the use of SAR-derived observations to detect eddies, surface temperature-related features and river and estuarine plumes can aid NMFS in the management of fisheries in subtropical and tropical regions where uniform sea surface temperatures preclude AVHRR measurements of surface structure, and cloud cover obscures ocean color observations.

10.6. Enforcement and Surveillance

a. Definition

The Enforcement and Surveillance category addresses applications dealing with the enforcement of laws, regulations and treaties, and surveillance, as it applies to intelligence gathering and monitoring events affecting National security. No classified applications are described in this report.

b. Feature and Change Detection

The DEA can utilize SAR-derived observations of domestic and foreign regions to detect clandestine drug laboratories, and airfields using feature detection techniques, while SAR-derived change detection methods may permit the monitoring of activity levels at clandestine airfields and other drug transportation hubs. SAR observations can also be used to confirm HUMINT and SIGINT information supplied on illegal drug manufacturing and transport.

c. Ships and Ship Wakes

The NOAA/NMFS, along with the USCG and ONI, can incorporate SAR-derived observations of ship and ship wakes into other observational data to aid in identifying illegal fishing activities (Figure 10-33) within the U.S. EEZ, making more efficient aircraft and patrol vessel reconnaissance activities.

The USCG and ONI, in support of counter-drug operations, detection and interdiction of illegal aliens, (Figure 10-34) illegal transport and landing of weapons, and counterfeit consumer commodities can benefit from the use of SAR-derived observations of ships (Figure 10-35) and ship wakes (Figure 10-36), particularly under cloud cover and during nighttime conditions.

The ONI, in their support of United Nations Resolution 46/215, which established a moratorium on driftnet fishing on the high seas, may utilize SAR measurements of ships, wakes, and net signatures to aid in the detection and interdiction of these high seas fishing violations. Since these illegal operations generally occur under nighttime conditions, SAR provides a unique observational capability.

d. Cueing Tool

In many instances involving enforcement and surveillance applications, the civil space-based SAR measurements will contribute to a suite of observations being applied to specific applications, and may, in many instances, serve as a cueing tool for other sensors and assets.

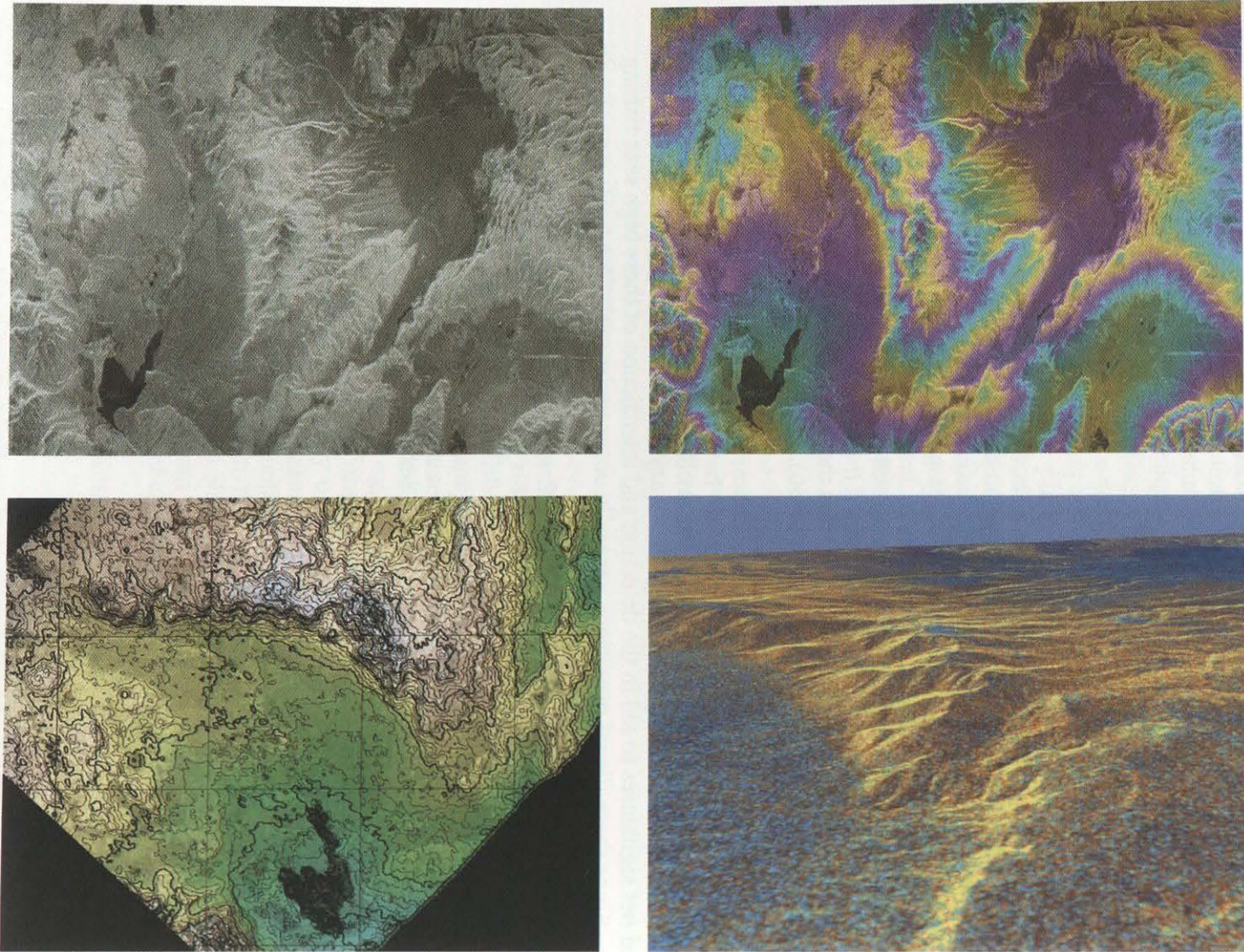


Figure 10-1. Long Valley region of east-central California acquired by SIR-C/X-SAR interferometer, illustrating processing steps from SAR image (upper left) to interferogram (upper right) to contour map (lower left) to perspective view (lower right).



Figure 10-2. Drug interdiction operations often require accurate terrain maps in areas of denied access for raid planning and execution. (Photo: Drug Enforcement Administration)



Figure 10-3. Terrain maps and charts of the littoral battlespace are required to support and execute amphibious assaults such as shown with this landing craft air cushion (LCAC) vehicle. (Photo: U.S. Department of Defense, Still Media Records Center)



Figure 10-4. SAR-derived images of the seabed topography in shallow water regions can aid in the planning and execution of minesweeping operations. (Photo: DOD, Still Media Records Center)



Figure 10-5. Navy Sea-Air-Land (SEAL) team insertion/recovery operations can be aided with SAR-derived images of the surf and beach regions. (Photo: DOD, Still Media Records Center)



Figure 10-6. SAR-derived contour maps can aid expeditionary warfare units in determining landmarks, lines of communication and trafficability. (Photo: U.S. Department of Defense, Still Media Records Center)

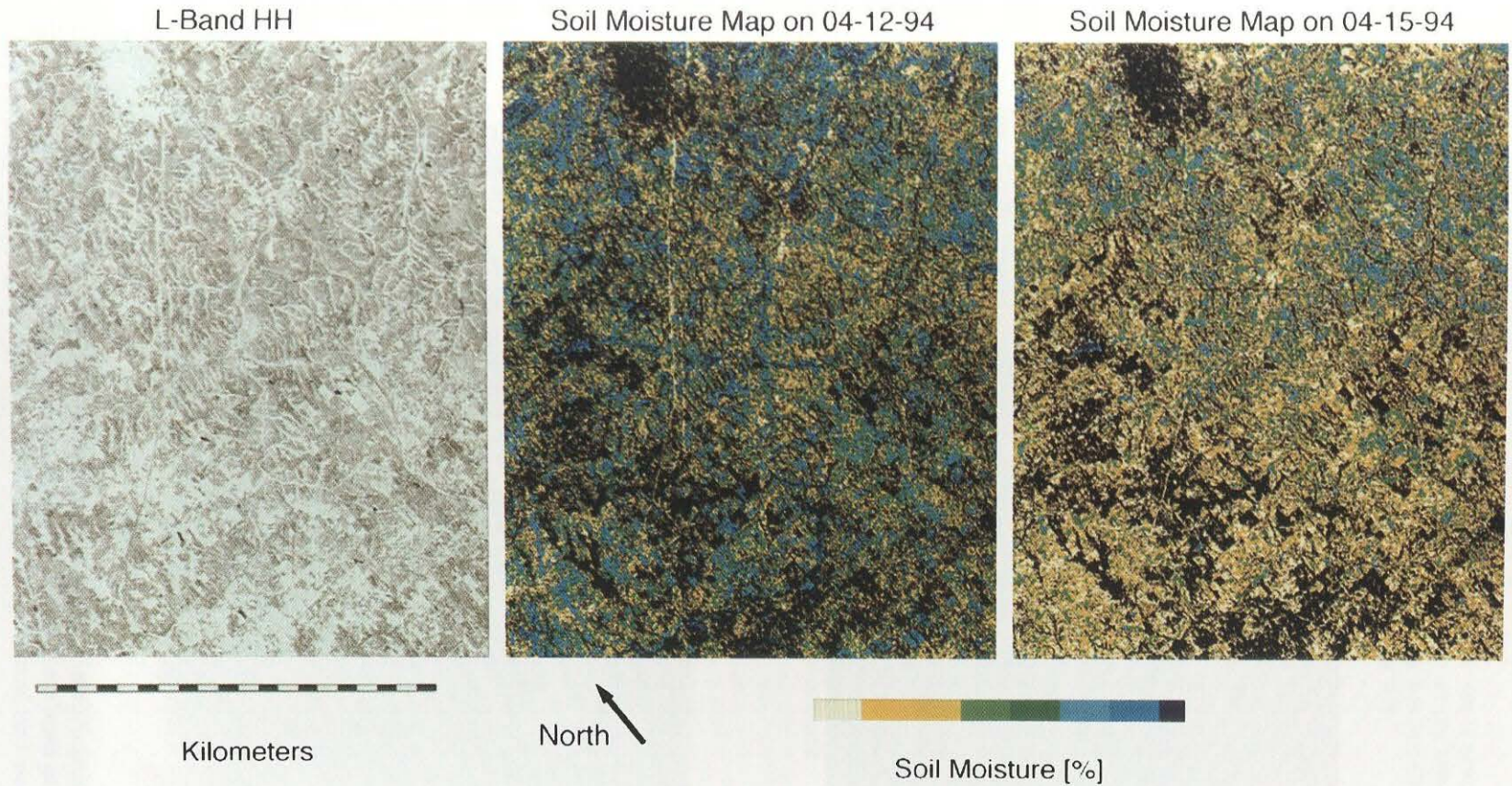
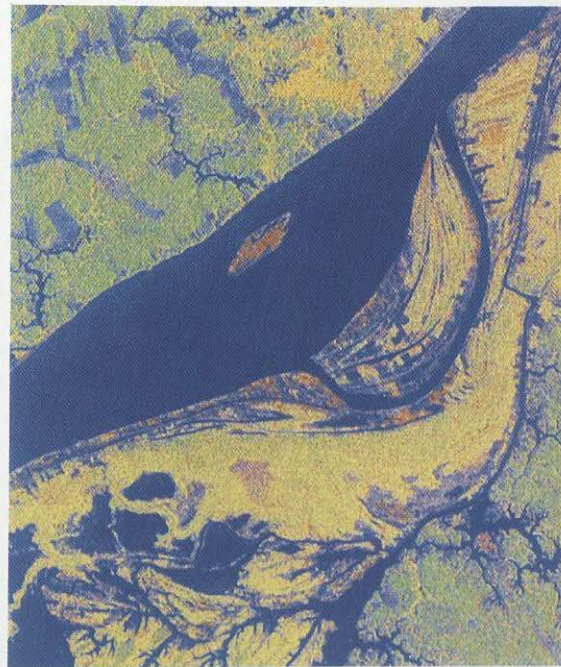
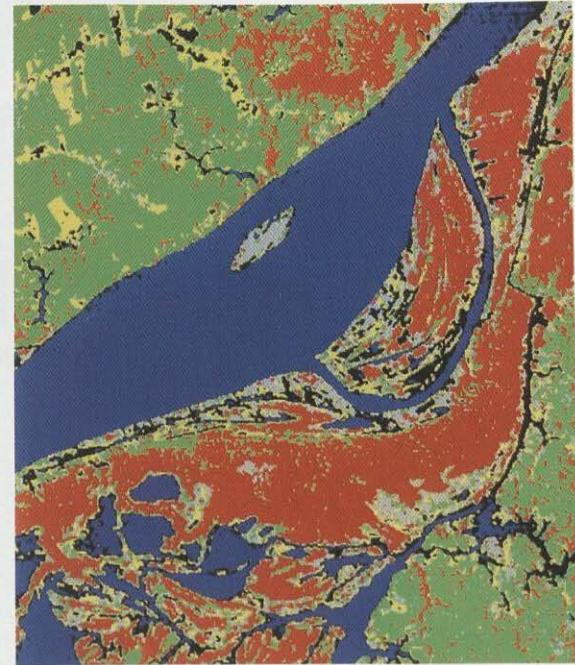
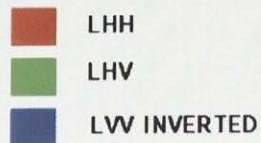


Figure 10-7. L-band HH image and two soil moisture maps of Chickasha, Oklahoma derived from SIR-C data in 1994. Soil moisture retrievals can aid in agricultural applications and military operations.



SIR-C IMAGE



INUNDATION MAP



Figure 10-8. Maps of the flooding and land cover from data obtained by the SRL-I mission showing the flood water inundation from the Rio Solimoes River in Brazil. The map uses the L-band HH, HV, and VV polarizations to classify the radar image into six categories. Flood damage assessment can be aided by the use of space-based, SAR-derived inundation maps on a global scale.

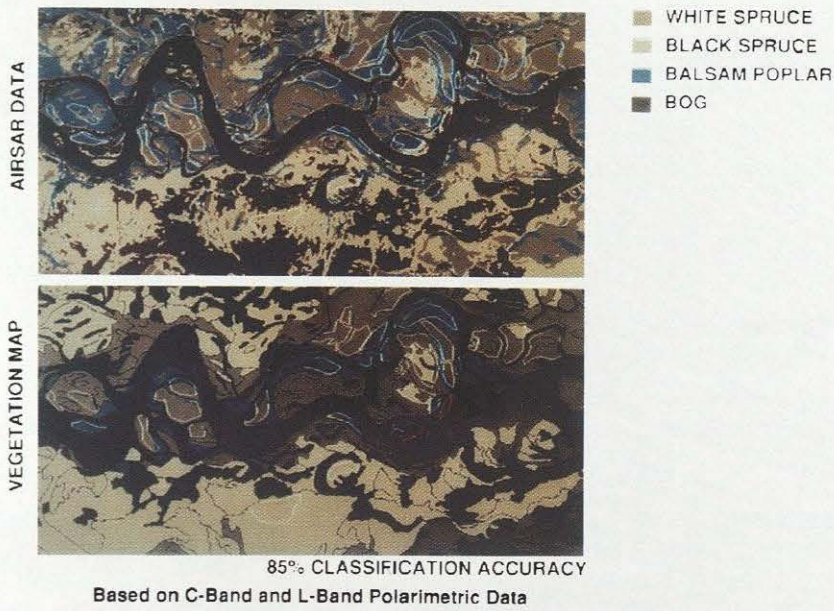


Figure 10-9. JPL AIRSAR images of Bonanza Creek, Alaska showing classification of natural vegetation/landcover. Such maps are important assets supporting forest fire fuel assessments and biological resource analysis.

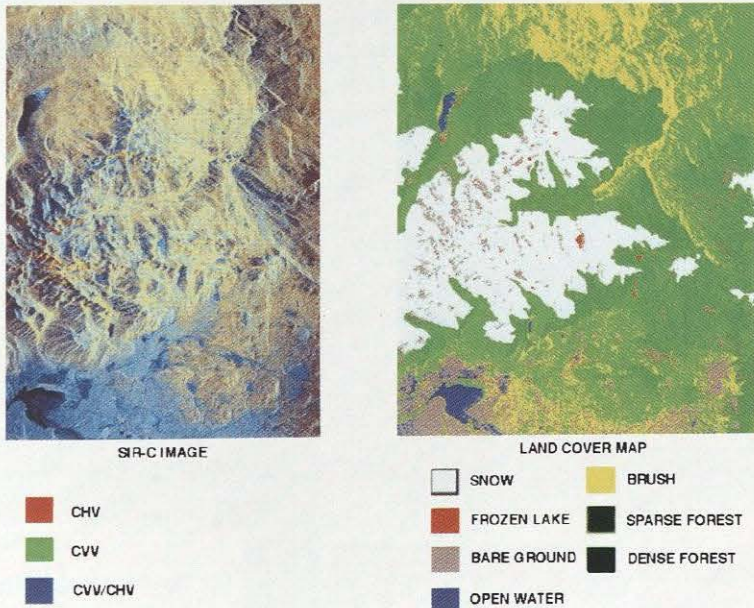


Figure 10-10. A land cover map derived from a SIR-C/X-SAR C-band image of Mammoth Mountain, California. Such maps can aid in the assessments of wildlife habitat, and agricultural land use patterns, particularly in cloud-covered regions.



Figure 10-11. SAR-derived agricultural crop classification map based on multipolarization measurements. Such maps can assist in crop inventory assessments important to various services with the U.S. Department of Agriculture.

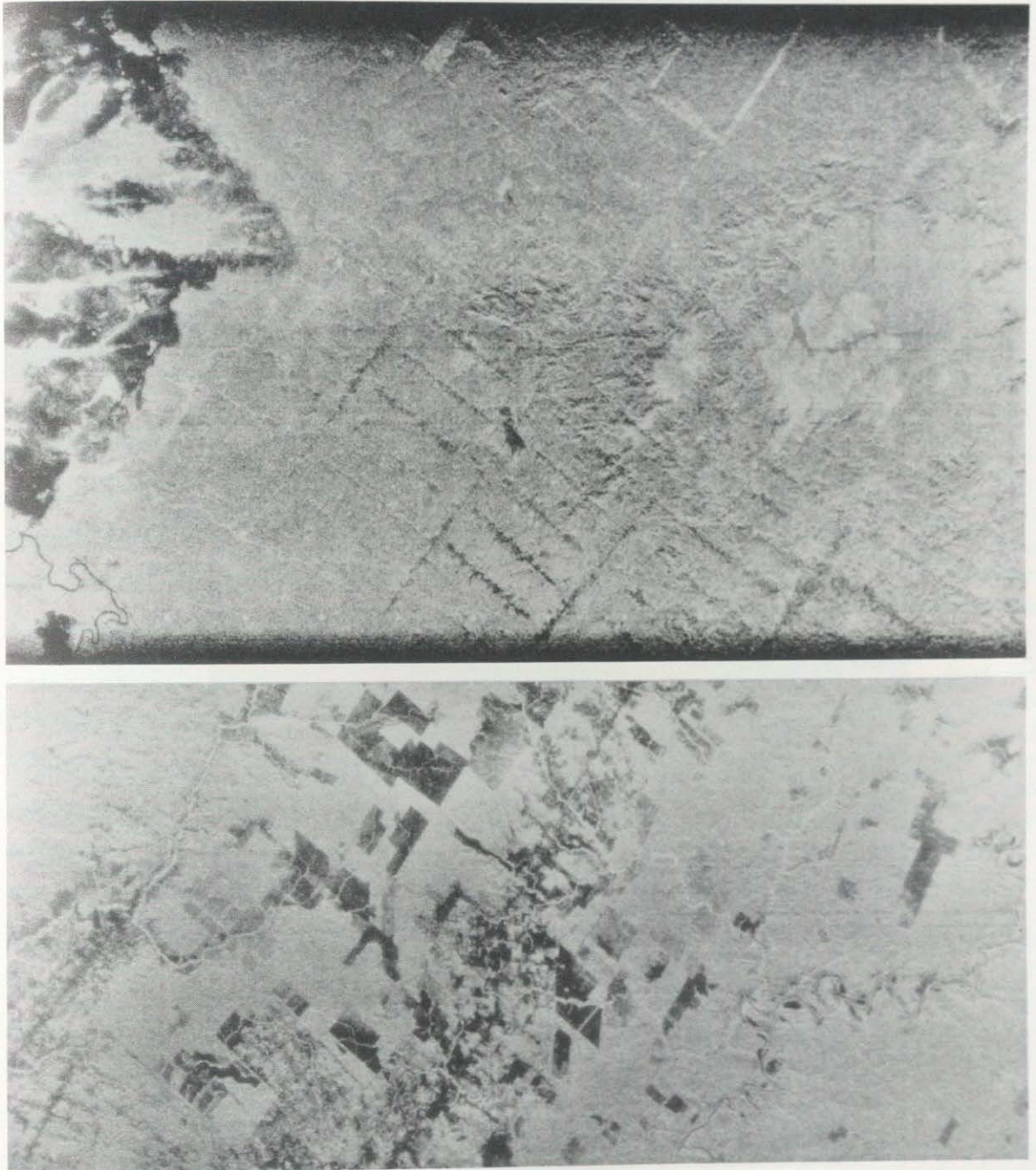


Figure 10-12. SAR-derived image of the Amazon Basin showing land cover and regions of deforestation.

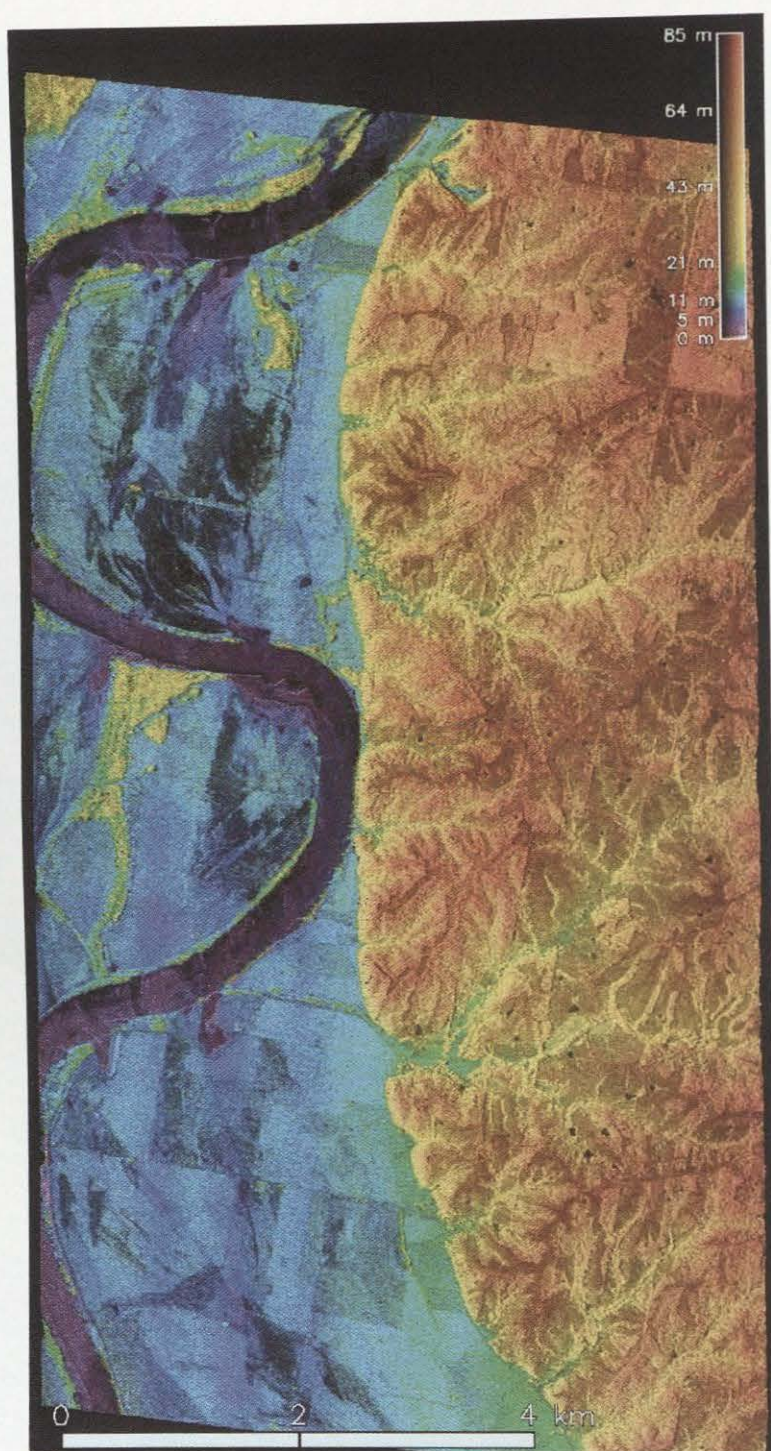


Figure 10-13. A combined radar and topography image of the Missouri River that experienced severe flooding and levee failure in 1993, acquired by the NASA/JPL (TOPSAR) system in 1994. The colors in the image represent elevations. The river's flood plain was completely inundated during the flood of 1993. Dark streaks and bands in the flood plain are agricultural areas that were severely damaged by levee failures. An outburst of water from a failed levee scoured a deep channel across the fields, which shows up as a purple band.

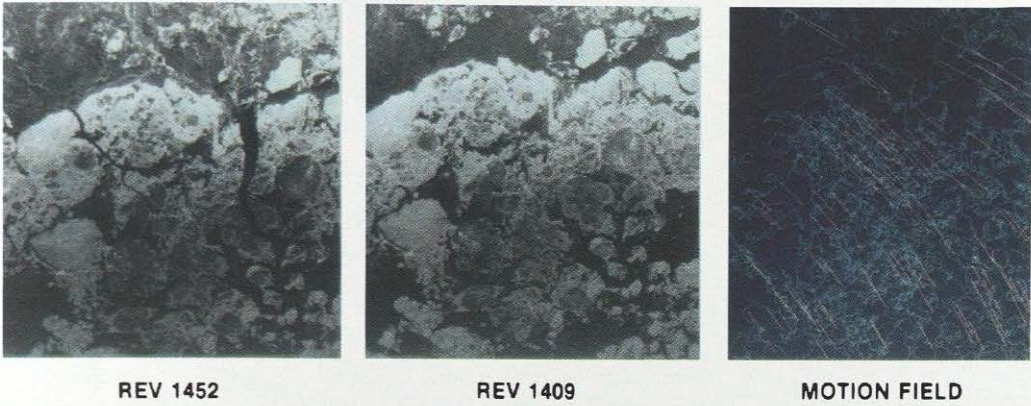


Figure 10-14. A map of sea ice motion derived from SEASAT SAR observations obtained during successive orbits in the Beaufort Sea. Such maps can provide important information on sea ice dynamics in Arctic regions for off-shore oil and gas operations, as well as Arctic ship routing, icebreaker operations and under-ice submarine safety management.

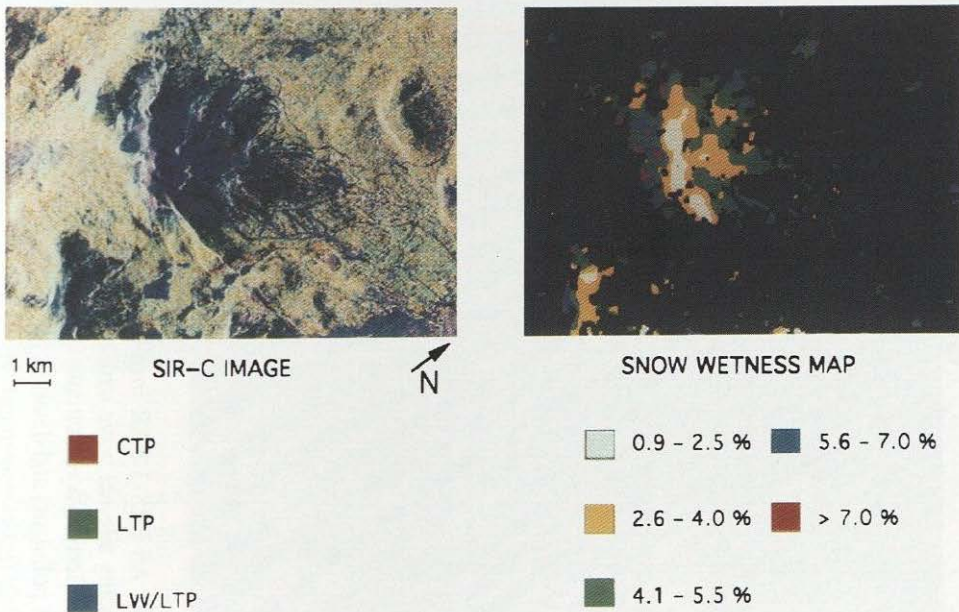


Figure 10-15. A snow wetness map derived from a SIR-C C-band multipolarization image of Mammoth Mountain in California's Sierra Nevada mountain range. Such maps can aid in determining snow-water equivalence to support water supply forecasting and hydroelectric power management.

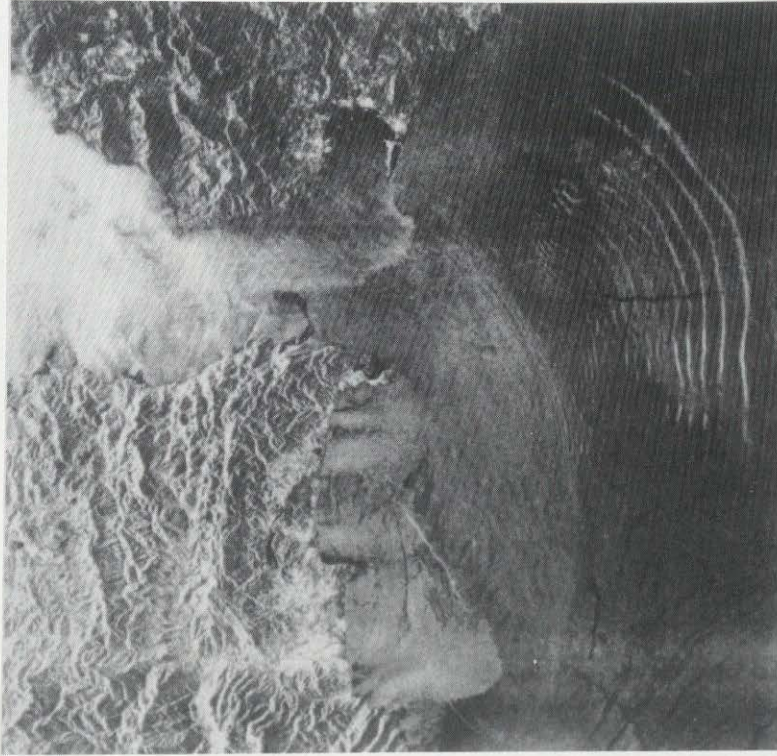


Figure 10-16. An ERS-1 SAR image of ocean circulation patterns, including internal wave structure, in the Straits of Gibraltar. SAR-derived ocean circulation observations can aid in the tracking of pollutants and determining transport mechanisms important in fisheries management applications. (Photo: ESA)



Figure 10-17. An ERS-1 SAR image of the mouth of the Seine River on the English Channel showing the river outflow which is controlled by seawalls. (Photo: European Space Agency and the Defence Research Agency-Farnborough)

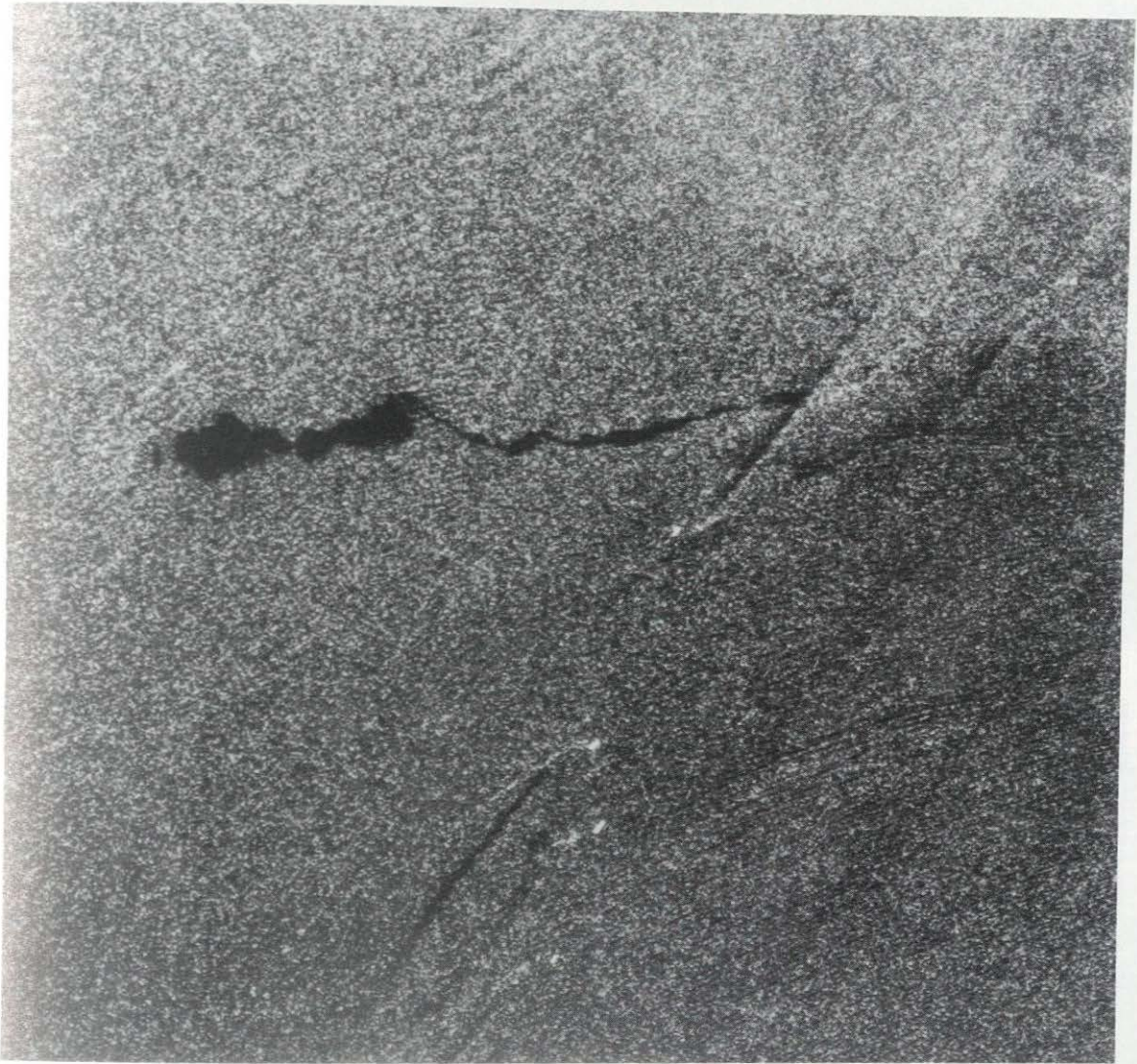


Figure 10-18. AN ERS-1 SAR image of a large oil slick off the west coast of Norway.
(Photo: Forsvarets Forskningsinstitut, Kjeller, Norway)

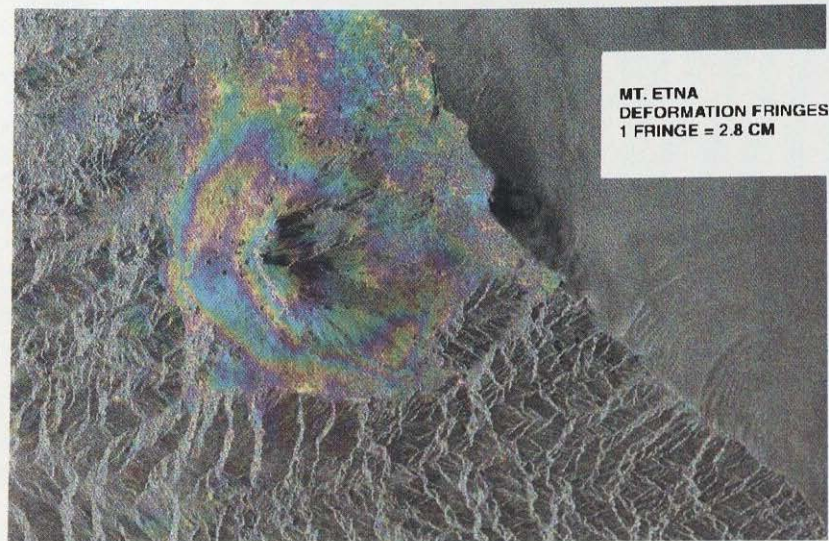
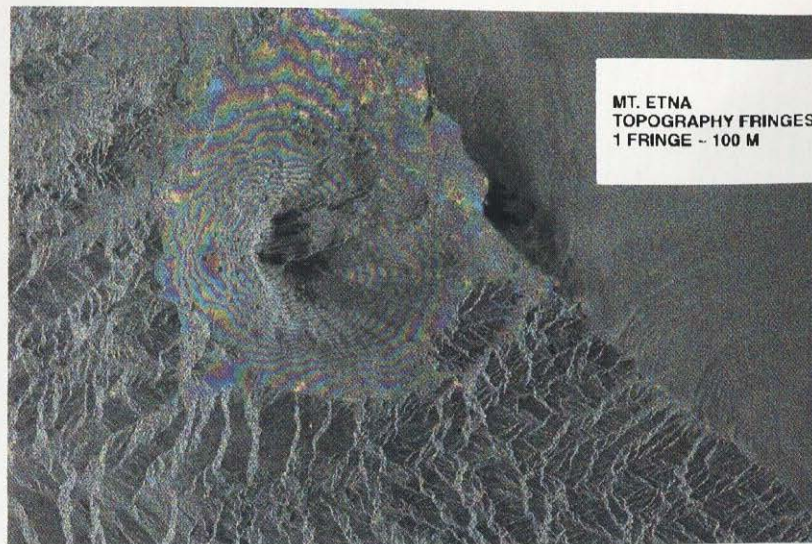


Figure 10-19. These two panels illustrate inference of volcano topography and deflation maps generated from interferometric synthetic aperture radar data acquired over Mt. Etna, Sicily. Top: produced from a single pair of ERS-1 images showing topographic contours at ~100 meter spacing. Bottom: a combination of three passes reduced to give deflation of the volcano over a one year period near the end of the latest eruptive cycle. Etna deflated by ~14 cm peak over this period. (Photo: Stanford University and ESA)

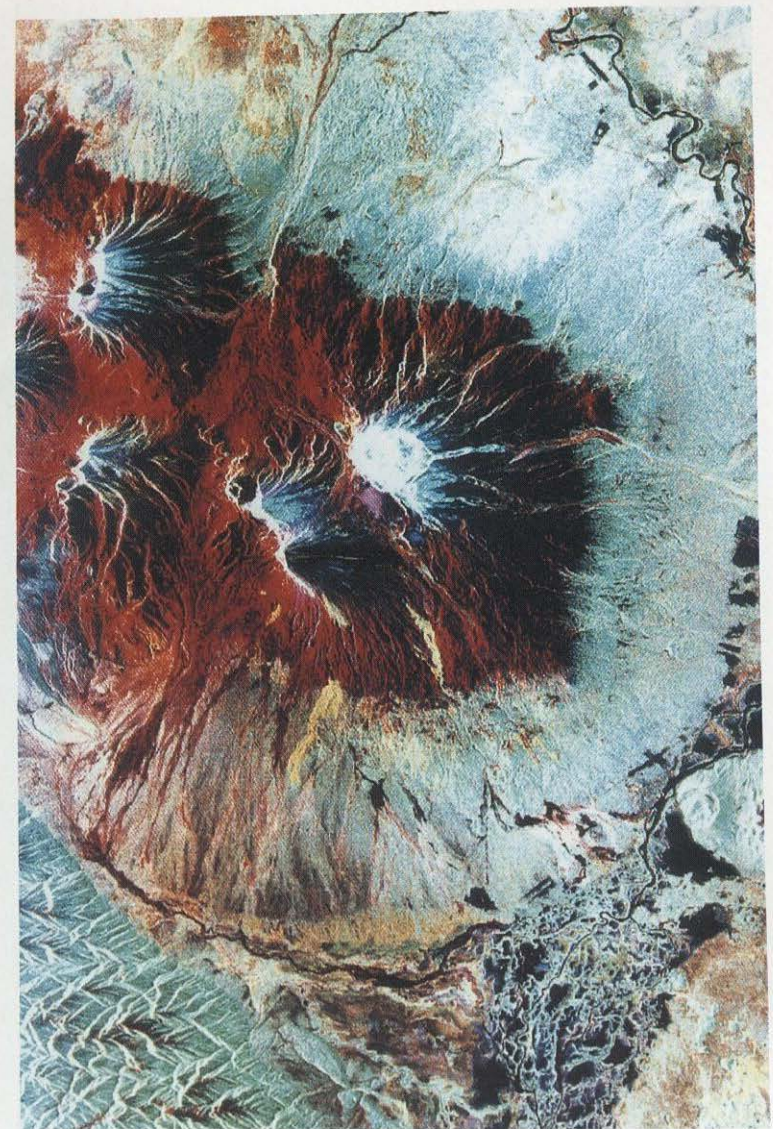


Figure 10-20. A SIR-C/X-SAR image (composite of L and C-bands) of the Kliuchevskoi volcano, Kamchatka, Russia (blue triangular peak in the center) which erupted in 1994. Melting snow mixed with volcanic ash triggered mudflows on the flanks of the volcano shown as thin lines in various shades of blue and green on the north flank in the center of the image. Two other active volcanoes are visible in the image.



Figure 10-21. SAR image data can aid in supporting post-earthquake damage assessments such as shown in this photograph of structure damage resulting from the Northridge, California earthquake in 1993. (Photo: FEMA)

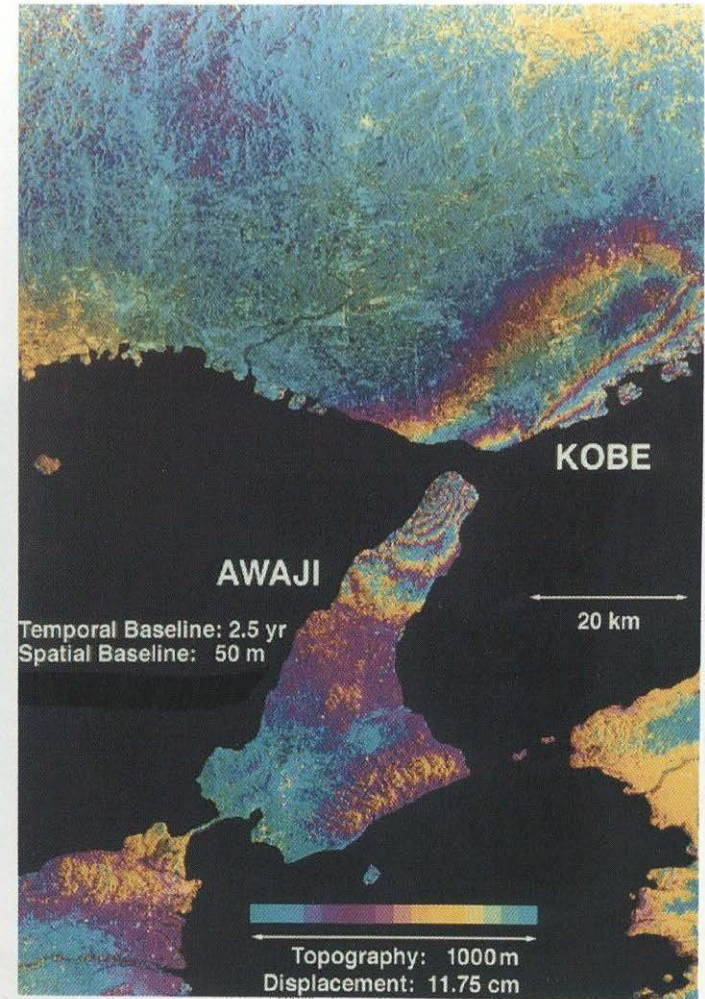


Figure 10-22. A JERS-1 interferometric image of the Kobe, Japan area following the 1995 earthquake, depicting the surface features changed due to earthquake damage. This illustrates the potential of interferometric SAR to aid in post-earthquake damage assessment. (Photo: JPL, GSI and NASDA)

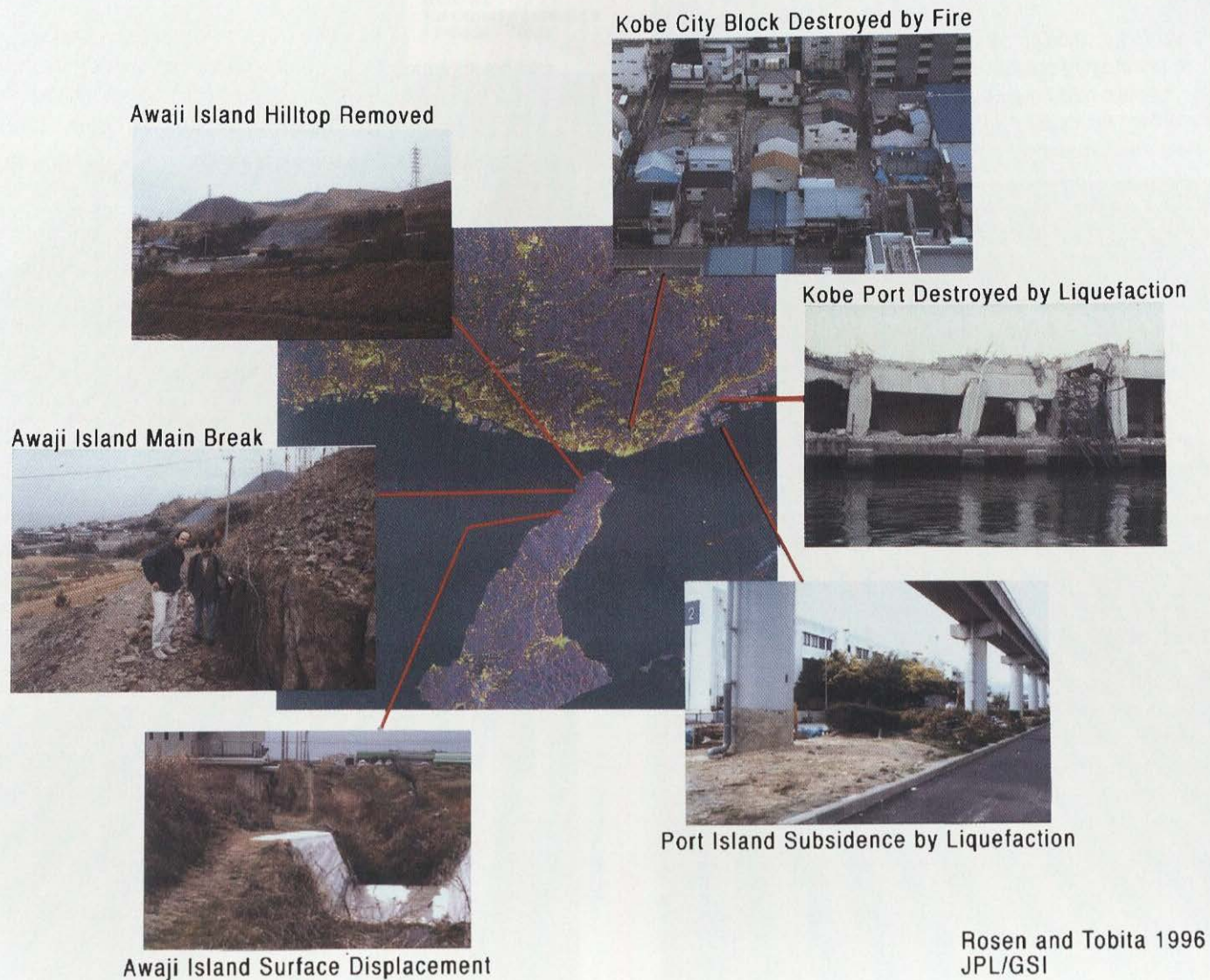


Figure 10-23. 1995 Kobe earthquake correlation signature, JERS-1 L-band interferometry for damage assessment. (Photo: JPL and GSI)



Figure 10-24. SAR observations of flooded regions, such as shown in this photograph of flood conditions from the Missouri River, can aid in the assessment of flood extent, flood water levels, damage to crops, local population, and industries. (Photo: FEMA)

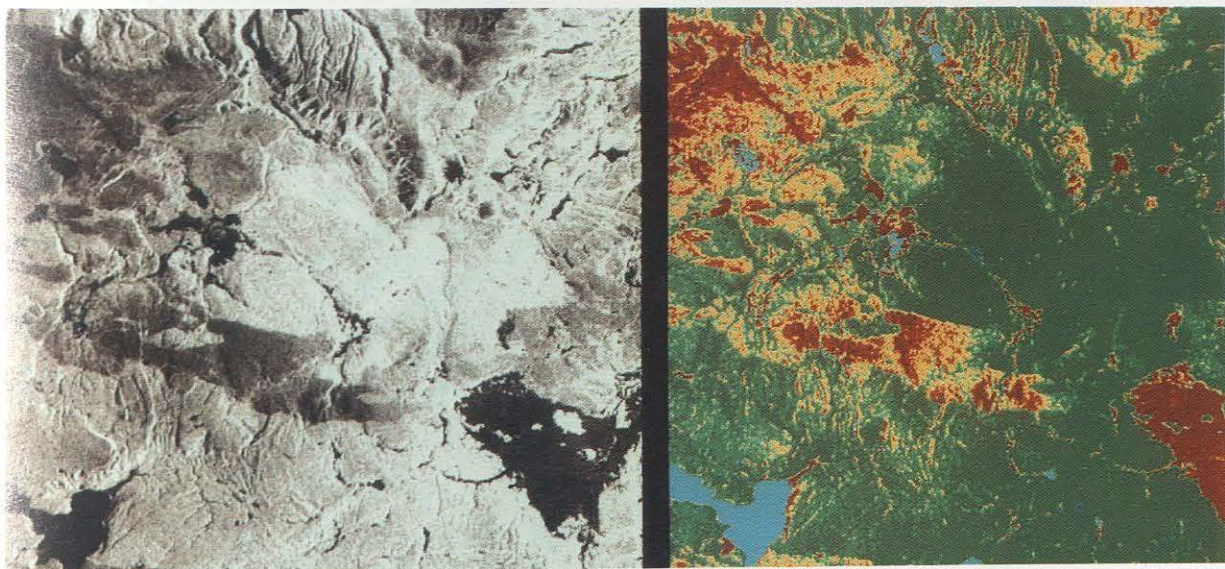


Figure 10-25. Two SIR-C/X-SAR L-band images of Yellowstone National Park, Wyoming obtained in 1994, six years following a major fire in 1988. At right is a map of the forest crown showing its biomass. The map is displayed on a color scale from blue (rivers and lakes with no biomass) to brown (non-forest areas with crown biomass of less than 4 tons/ha) to light brown (areas of canopy burn with biomass of between 4-12 tons/ha). Yellow indicates areas with a biomass of 20-35 tons/ha; and green is forest with a biomass of greater than 35 ton/ha). SAR measurements of fire-affected regions can clearly aid in monitoring forest regrowth after a fire.



Figure 10-26. SAR image data of sea ice conditions can aid in supporting icebreaker operations in Arctic regions by identifying thin ice and open water regions in order to reduce transit times and propeller damage. (Photo: U.S. Coast Guard)



Figure 10-27. SAR image data of lake ice conditions permits more efficient icebreaker operations and vessel traffic management during heavy ice seasons in the Great Lakes. (Photo: U.S. Coast Guard)



Figure 10-28. An ERS-1 SAR image of Arctic sea ice, classified in terms of ice type, open water and polynyas. Such classification maps permit the determination of optimum routes in support of vessel navigation in ice infested waters. (Photo: European Space Agency)



Figure 10-29. SAR observations of sea ice under all weather conditions, and ice classification maps can be key tools in reporting ice characteristics and lead locations to submarine commanders in under-ice operations to support submarine safety. (Photo: U.S. Department of Defense, Still Media Records Center)

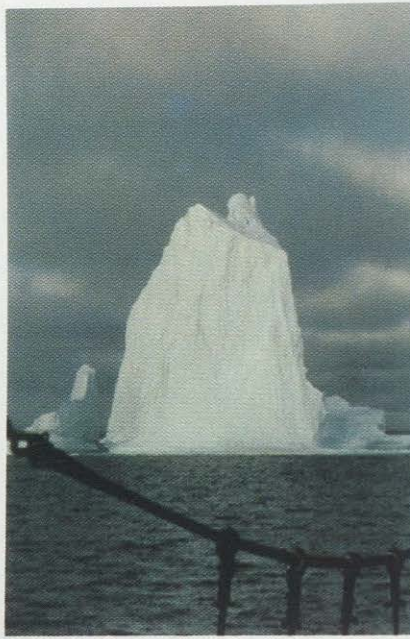


Figure 10-30. The detection and tracking of icebergs is essential for safe navigation of North Atlantic shipping lanes. The USCG International Ice Patrol provides reconnaissance to monitor iceberg locations and report the southern limits of all known icebergs to vessels at sea. SAR observations of iceberg regions may permit more efficient surveillance and reporting operations. (Photo: U.S. Coast Guard, International Ice Patrol)



Figure 10-31. A NOAA AVHRR image depicting the Gulf Stream sea surface temperature (left) overlaid with an ERS-1 SAR image (right) showing the frontal walls of the current structure. (Photo: European Space Agency)



Figure 10-32. An ERS-1 SAR image of the English Channel north of the Thames River. Surface structure observed in the Channel is related to the seabed topography. Such imagery can aid in monitoring changes in shoals and sandbars, as well as providing input to littoral models supporting military expeditionary warfare operations. (Photo: European Space Agency and the Defence Research Agency-Farnborough)



Figure 10-33. SAR observations of surface ships and their wakes can aid in the detection of illegal fishing activities and make more efficient reconnaissance activities in the U.S. EEZ. (Photo: U.S. Coast Guard)



Figure 10-34. SAR observations of surface ships and their wakes can aid in the surveillance and interdiction of illegal activities, including illegal entry of aliens. (Photo: U.S. Coast Guard)

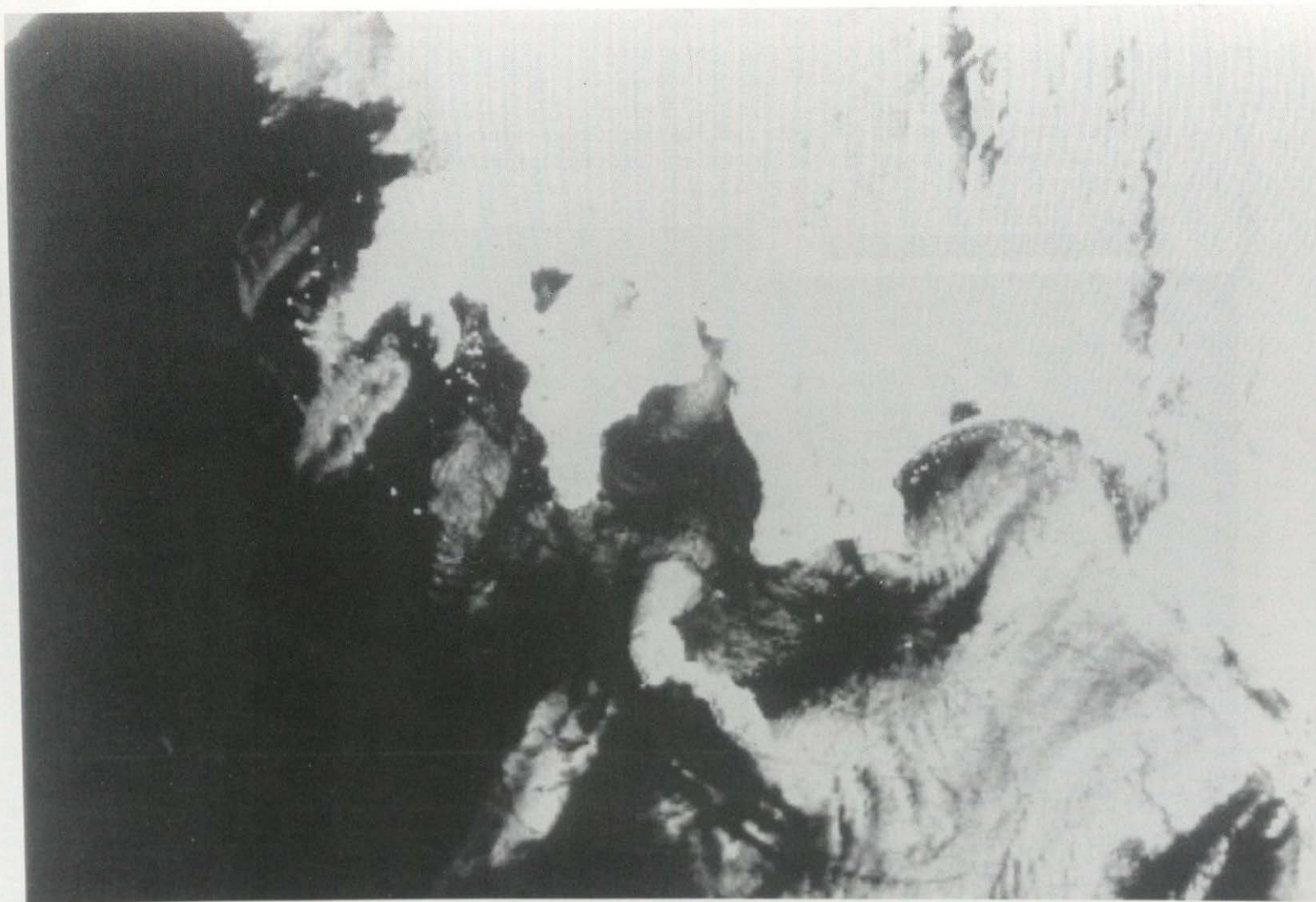


Figure 10-35. An ERS-1 SAR image of Togiak Bay, Alaska showing the location and extent of fishing vessels operating in the area.
(Photo: European Space Agency)

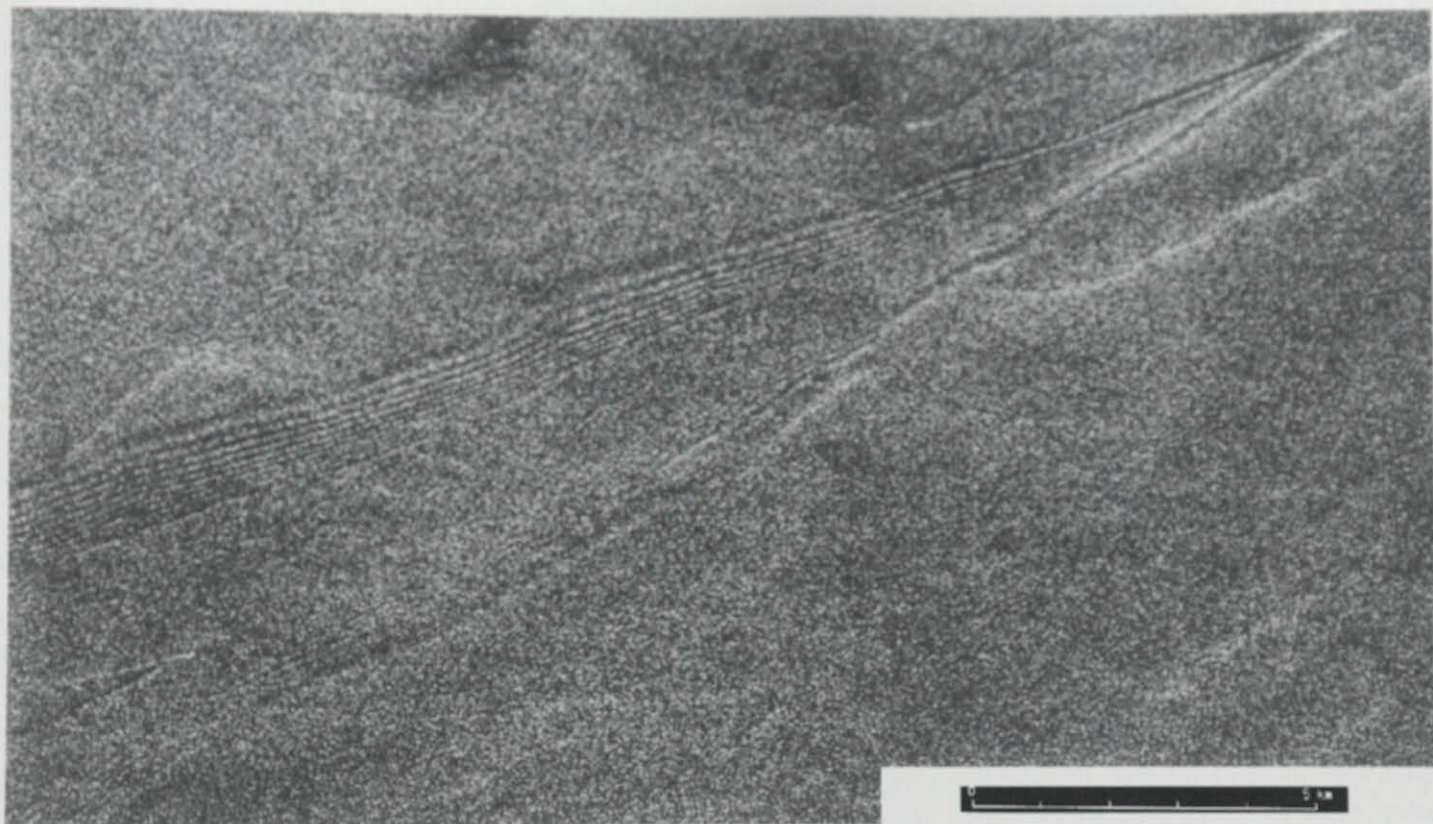


Figure 10-36. An ERS-1 SAR image of a significant ship wake, illustrating the structure that can often be observed in the wakes of surface ships under optimum sea conditions. (Photo: European Space Agency and the Forsvarets Forskningsinstitut, Kjeller, Norway)

11—SAR Data Processing and Distribution

a. Data Processing

As discussed previously, the technology exists today to process space-based SAR in real time to provide "keep-up" capability for operational users. Such systems are becoming affordable and, for the most part, utilize commercial, off-the-shelf hardware and processing algorithms. While this capability now exists, most ground stations currently in place and operational do not have this level of SAR processing capability. The Alaska SAR Facility, the Canadian station at Gatineau, and the Norwegian station at Tromsø will have the capability to process RADARSAT data at roughly one-tenth real time to support operational applications. Other ground stations capable of receiving SAR data from civilian satellites have much slower processing capabilities, and some stations are collection/recording facilities only. For operational applications within the Continental United States (CONUS), Alaska and Arctic regions, existing ground stations can provide the necessary coverage and limited processing capability. For global applications, few, if any, ground stations can provide the needed throughput capacity. Tape recorders on RADARSAT and some future SAR satellites, will provide a limited capability to collect global data, which can be played back to selected ground stations for processing - thus providing a near-real time capability. Overall, the SAR processing capability at existing ground stations in support of operations is bleak. In the near term, many operational users state that they will require ground stations covering the CONUS and Alaska to provide near-real time (within 1 hr.) processing for RADARSAT, ERS-1 and ERS-2 SAR data. For global applications (excluding the Arctic regions), utilizing these satellites, it is unrealistic to expect foreign ground station support. The use of either the satellite tape recorders, where supplied, or transportable ground stations which include near-real time SAR processors, will be essential to support operations.

Transportable ground stations, without SAR processors, are deployed in the Antarctic, Africa and Mongolia, and new systems are being manufactured now in the U.S. and Canada. In the longer term, operational requirements for SAR data will spread over a sufficiently broad range of applications, placing severe demands on centralized SAR processing systems. Selective on-board processing of SAR data, together with data compression techniques and direct downlink transmission capabilities, will provide data to users in sufficient time to support nearly all time-critical operations where data are perishable. Operational user requirements will set the pace for the use of field-deployable transportable ground receiving and processing systems, and the incorporation of on-board SAR processing and direct downlink systems on SAR satellites beginning in the 2000 time frame.

b. Data Distribution

Some operational applications of SAR data can be supported with data processed and distributed in days or weeks following the observations. Such non real-time data requirements can be satisfied from data archives using either computer browse and file transfer systems, or tapes/CDs/optical discs forwarded from the archives to the user by mail or express package delivery systems. The distribution of SAR data by these means is reliable and costs are minimal. Because of the perishable nature of the data, or the time-sensitive nature of the application, many operational users require SAR data delivered to their operational centers or field sites in near-real time. Where centralized SAR processing occurs separately from the users facilities, wide-band communication circuits connecting the processing center with users facilities, are required to accommodate the large quantities

of digital image data. Even within the U.S., these circuits are expensive, and, for international connections, the costs may be prohibitive. In some applications, these wide-band communication pathways are essential and, once again, the use of onboard SAR processing and data compression methods can minimize the bandwidth requirements for interconnecting communications circuits. In other applications, these costs can be avoided through the use of either transportable or fixed tracking, receiving, and processing facilities where analysts are on site for image analysis and interpretation. Onboard SAR processing and data compression techniques are requirements for future space-based SAR systems which support operational users.

12—Satellite Tasking

The ability to task SAR satellite systems to take specific observations necessary to support operations is an essential requirement of operational users. In some applications, particularly those involving topographic mapping and routine monitoring of land features and enforcement-sensitive ocean areas, this tasking can often be defined weeks prior to the desired observations. However, in many applications, tasking requirements are not known until a few days or hours before the observations are required. Perishable data, time-sensitive military, enforcement, and intelligence operations, environmental emergencies, and threats to national security are all examples of applications requiring rapid tasking of SAR satellite systems. For U.S.-owned satellites, provisions for such rapid tasking may well be accommodated through the interagency development of protocols and priorities to be applied by system users. For foreign-operated satellites, developing such tasking provisions can be a formidable, if not impossible task, and may well be a barrier to the operational use of international SAR satellites as envisioned in the SAR-2000 concept. Future SAR satellite initiatives must recognize and accommodate the tasking requirements of operational users, and build highly focused coordination schemes into ground system protocols and command link structures to provide rapid response to tasking requests on the order of 2 days to 8 hours.

13—Training

SAR image data are a new and unique data type for many operational users, including those users who have been using electro-optical remotely sensed data to support operations. For such users, training in the analysis and interpretation of SAR image data is essential to the incorporation of space-based SAR data into the mission applications of operational users. This training is especially important to operational users where analysts typically rotate in assignments, such as is the case for military and some intelligence users. With these rotations, new analysts are assigned to SAR-based tasks and SAR training is necessary for them to be proficient in their assignments. Formal SAR training courses must be developed and made available to operational users, both as introductory SAR training for users new to remote sensing and those familiar with remote sensing, but new to SAR. Refresher training is also needed to update users on new sensor, processing, and algorithm capabilities. Training should include instruction in SAR principles, examples of operational applications, application of data extraction and derived-product algorithms, data blending methods, and hands-on instruction in image analysis and interpretation tailored to the specific applications of the users' operations. A long-term commitment to SAR training is essential to support operational users and may well represent an opportunity for a private-sector business venture.

14—Recommendations

It is the consensus of the Interagency Ad Hoc Working Group on SAR that space-based SAR data can provide unique information and observational capabilities that should be exploited to support operational applications. While SAR data represents a relatively new data type, particularly to civilian agency users, its use by some military and intelligence users is now routine due to the operational use of airborne SAR systems. Emerging applications are being defined in the areas of mapping and charting, resource monitoring and management, pollution and waste threats, detection and mitigation of natural hazards, coastal ocean and ice operations, and enforcement and surveillance missions.

Fully exploiting the potential of civilian space-based SAR systems to support operations requires careful consideration of a number of critical and sometimes conflicting factors, including the following:

1. Because of the perishable nature of data and/or the time-sensitive character of the applications, many operational users require SAR data in their operational centers in near-real time (1-6 hours following the SAR observations). These needs place demanding requirements on SAR data processing systems and communication pathways. To support operational users, future civilian space-based SAR systems, in addition to providing a data stream which preserves the radar phase histories, must incorporate parameter-oriented onboard processing systems, data compression capabilities and direct downlink communication systems, while ground receiving and processing stations must have SAR processors with "keep-up" capability.
2. Many operational users are unable to define their specific observational requirements with long lead times (weeks to months). Only when unplanned events (natural disasters, environmental hazards, search and rescue missions, national security threats, etc.) or late-occurring observations or intelligence reports are obtained, can some users specify an observational need and satellite tasking requirement. Consequently, for many operational users, it is required that satellite tasking be possible within days or hours prior to the observation opportunity. This requirement presents significant challenges to mission planning protocols and priority definitions, and may be a barrier to the use of foreign satellites for some operational users.
3. To establish an operational capability for new remotely sensed data, most users must make substantial investments in the infrastructure of their operational centers, including hardware, software, communications, and training. The integration of SAR data into operations will demand such investments. Before committing to such investments, operational users must be assured of a continuity of data over a decade or longer. Therefore, future U.S. investments and participation in space-based SAR systems must provide for this data continuity, which is likely to imply that future SAR systems must involve multiple satellites whose launch dates and design life, collectively, provide a continuous source of SAR data spanning a decade or more.
4. In environmental satellite programs, there is a growing trend toward the commercial sale of Earth observation data. The ERS-1/2 and RADARSAT programs are examples of this. The cost of data can preclude new users from acquiring and exploiting remote sensing to support their missions. For operational users, any

data pricing policies in future SAR programs should include incentives (e.g., introductory rates) to encourage new users to acquire data initially, at affordable prices, in order to gain familiarity with the data and its cost effectiveness in operational use.

5. Many potential operational users of space-based SAR systems have yet to be acquainted with the capabilities of the single parameter (one frequency, one polarization) SAR satellites (ERS-1, ERS-2, RADARSAT), or the more powerful character of multi-parameter SAR, to support operations. SAR research results have not been described to these potential users and, while electro-optical remote sensing systems (i.e., Landsat, SPOT) are finding broad operational utilization, SAR remains a relatively unused source of remotely-sensed data supporting operations. For the full exploitation of SAR technology, an aggressive outreach program must be conducted to acquaint potential operational users with SAR principles, current and projected SAR sensor capabilities, and research/demonstration evidence to support SAR utilization in operational applications. Demonstration projects must be conducted to test the operational utility of space-based SAR, and to train operational analysts in the interpretation of SAR imagery.
6. As an element in the mechanism for transitioning research results to operations, there is a need to have a vigorous aircraft program which can provide for mini-campaigns where operational users can conduct demonstration projects which provide evidence of the utility of SAR in operational applications. Such mini-campaigns provide an early and affordable access to multiparameter SAR and create the learning experience needed for users to more explicitly define their requirements for, and applications of, space-based, multiparameter SAR.

In addition to the recommendations outlined above, the following summary recommendations represent the consensus of the Interagency Ad Hoc Working Group on SAR, in terms of future U.S. investments in civilian space-based SAR initiatives suited to the needs and applications of U.S. Agency operational users:

1. It is the consensus of the Working Group that the United States should make the necessary investments to develop, at the earliest possible date, a civilian SAR satellite capability with attributes necessary to support operational applications, including a SAR system which incorporates the following:
 - A. An interferometric capability to acquire high accuracy (DTED or better) terrain elevation data and provide change-detection measurements.
 - B. A multifrequency, multipolarization capability that would permit vegetation characterization and geologic mapping, as well as measurement of soil moisture and the extent of flooding.
 - C. A low frequency (L-band or lower) capability to permit the penetration of vegetation canopy.
 - D. A variable swath width.
 - E. A variable resolution ranging from medium (100 m) to very high (5 m).

To achieve this satellite capability, two possible options are recommended:

- Option 1: The development of an independent U.S. satellite system with performance attributes required to support operations. As an independent U.S. system, under full U.S. control, it is possible to design performance parameters suited to U.S. users, to achieve a U.S. dedicated tasking capability, and to accommodate sensitive applications of national importance.
 - Option 2: The development of a U.S. interferometric SAR satellite system which could be one element of an international SAR satellite constellation, comprised of SAR systems with a diversity of frequencies and polarizations arranged in orbits which permit, with proper data registration, the extraction of multifrequency, multipolarization measurements. This option affords a lower cost U.S. investment to achieve a SAR satellite capability to support operations at the sacrifice of full U.S. control over all design elements, mission operations, satellite tasking, and data access.
2. The Working Group recognizes the need to exploit near-term opportunities in order to broaden the use of SAR in operational applications and to maintain (even expand) the momentum and interest of the operational SAR user community. The Working Group recommends the following:
- A. Consideration should be given to a third flight of the SIR-C/X-SAR sensor configured for interferometric operation on a Shuttle Radar Laboratory (SRL) mission. Such a mission can acquire global digital terrain elevation data at high accuracy (DTED-2) to support national needs (DOD, DOI, DEA, FEMA) for mapping information.
 - B. The Interagency Ad Hoc Working Group on SAR continues to serve as a forum for operational users of SAR data, where operational SAR requirements can be further defined and documented, where new applications can be identified and results shared, where SAR activities (aircraft and satellite) can be coordinated, and where SAR research needs and product development requirements of the operational community can be defined for research investments.

APPENDIX A ACRONYMS AND TERMS

AFB	Air Force Base
AIRSAR	Airborne Synthetic Aperture Radar
AMI	Active Microwave Instrument
ASF	Alaska SAR Facility
ASW	Antisubmarine Warfare
BIA	Bureau of Indian Affairs
BLM	Bureau of Land Management
CCRS	Canadian Centre for Remote Sensing
CINF	Community Imagery Needs Forecast
CONUS	Continental United States
CSA	Canadian Space Agency
DEA	Drug Enforcement Administration
DTED-2	Digital Terrain Elevation Data
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of Interior
EEZ	Exclusive Economic Zone
ERS-1, ERS-2	European Remote Sensing Satellite
ESA	European Space Agency
FEMA	Federal Emergency Management Agency
GTM	Global Topography Mission
HRPT	High Resolution Picture Transmission
HUMINT	Human Intelligence
IFSAR	Interferometric Synthetic Aperture Radar
ICEC	Ice Centre Environment Canada
JERS-1	Japanese Earth Remote-Sensing Satellite
JPL	Jet Propulsion Laboratory
Landsat	Land Satellite
LCAC	Landing Craft Air Cushion
MIZ	marginal ice zone
MMS	Minerals Management Service
MTPE	Mission to Planet Earth
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency (Japan)
NAVOCEANO	Naval Oceanographic Office
NBS	National Biological Survey
NESDIS	National Environmental Satellite Data and Information Services
NIC	National Ice Center
NMFS	NOAA National Marine Fisheries Service

NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NRL	Naval Research Laboratory
NSF	National Science Foundation
NSORS	NOAA Satellite Ocean Remote Sensing Program
ONI	Office of Naval Intelligence
ONR	Office of Naval Research
OSB	Ocean Studies Board
RADARSAT	Radar Satellite
RSI	RADARSAT International
SAA	Satellite Active Archive
SAR	Synthetic Aperture Radar
SCANSAR	Scanning Synthetic Aperture Radar
SEAL	Sea-Air-Land
SIGINT	Signal Intelligence
SIR-A, SIR-B	Shuttle Imaging Radar-A , -B
SIR-C/X-SAR	Spaceborne Imaging Radar-C/X-Band Synthetic Aperture Radar
SLARS	Side-Looking Airborne Radars
SPOT	Système Probatoire d'Observation de la Terre
SRL-1, -2, -3	Space Radar Laboratory 1, 2, 3
SRTM	Shuttle Radar Topography Mapper
TM	Thematic Mapper
TOPSAR	TOPographic Synthetic Aperture Radar
U.S.	United States
USCG	U.S. Coast Guard
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USF&WS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey