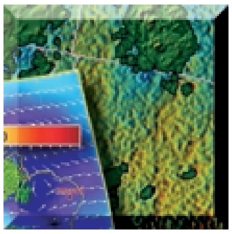

NOAA CoastWatch SAR Applications and Demonstration

William G. Pichel and Pablo Clemente-Colón

The goal of the National Oceanic and Atmospheric Administration (NOAA) CoastWatch Program is to provide satellite and other environmental data and products for near–real-time monitoring of U.S. coastal waters in support of environmental science, management, and hazard response. During the last few years, products available through CoastWatch have expanded beyond the original infrared, visible, and sea surface temperature images to include ocean color, scatterometer wind, and synthetic aperture radar (SAR) images. A NOAA research and development program with partners in government, academia, and industry has endeavored to develop coastal ocean SAR applications for CoastWatch. Some of these applications, in particular wind measurement and hard target (i.e., vessel) detection, were developed for a preoperational demonstration. Users include the NOAA National Weather Service, the Alaska Department of Fish and Game, and the U.S. Coast Guard. (Keywords: CoastWatch, SAR, Vessels, Winds.)

INTRODUCTION

This article describes the status and plans of a preoperational applications demonstration of coastal ocean synthetic aperture radar (SAR) imagery and products that began in the fall of 1999 in Alaska. This "Alaska SAR Demonstration" is first presented within the context of the National Oceanic and Atmospheric Administration (NOAA) CoastWatch Program. The key operational users are then introduced, followed by a description of the initial demonstration products. An outline of the data flow concludes the description of the demonstration.

COASTWATCH

CoastWatch is a NOAA activity managed by the National Environmental Satellite, Data, and Information Service (NESDIS) with CoastWatch "nodes" located at NOAA laboratories and offices in coastal states (see Fig. 1). The core mission of CoastWatch is to provide satellite (and other environmental) data and products for near–real-time monitoring of U.S. coastal waters in support of environmental science, management, and hazard response.

The CoastWatch nodes receive products from NESDIS or generate them locally. These products are then

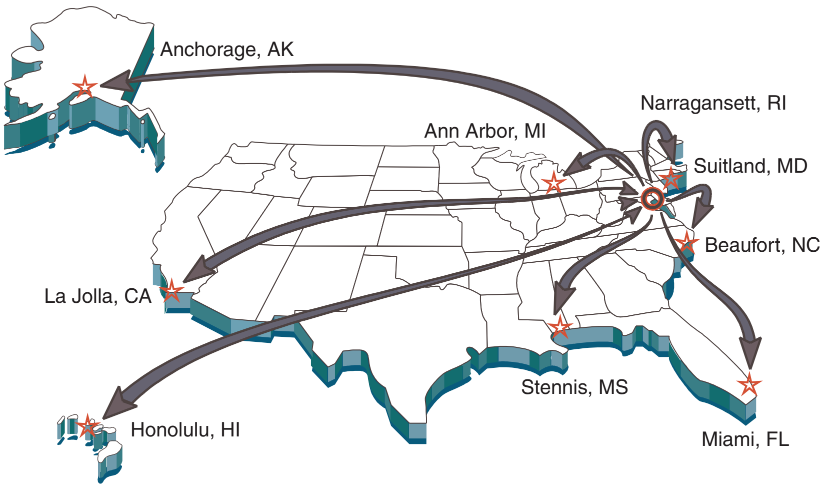

Figure 1. Location of the central CoastWatch node (Suitland, MD) and eight regional nodes. (Figure courtesy of Kent Hughes of NOAA/NESDIS and the CoastWatch Program.)

made available to a diverse and growing user community of federal, state, university, secondary school, and industry environmental resource managers, research scientists, educators, students, marine enthusiasts, and commercial marine enterprises. Satellite products include polar and geostationary satellite infrared, visible, and sea surface temperature (SST) images as well as ocean color and SAR imagery.

Established in 1990, with all eight nodes operating by 1993, CoastWatch now has over 4000 registered users. CoastWatch data and products are accessible in near–real time via Web sites at each node (see the CoastWatch home page at http://coastwatch.noaa.gov). The NOAA National Oceanographic Data Center (NODC) maintains the CoastWatch SST and polar-satellite infrared and visible image archive, providing another point of access to CoastWatch (particularly retrospective) data (see the NODC CoastWatch home page at http://www.nodc.noaa.gov/cwatch/ncaas-home.html). Most CoastWatch products are freely available over the Internet after registration with one of the CoastWatch nodes. The distribution of ocean color and SAR imagery data is restricted, however, to U.S. government agencies and their contractors or to those agencies and researchers participating in approved demonstration projects.

SAR imagery from the European Space Agency's European Remote Sensing satellites, ERS-1 and -2, and the Canadian Space Agency's Radarsat-1 have been used experimentally for several years at both the Alaska and Great Lakes CoastWatch nodes.[1] Applications of interest to CoastWatch are listed in Table 1.[2] Most fully developed are applications of SAR for sea/lake/river ice analysis and monitoring (denoted in Table 1 as "preoperational"). Three others are the subject of the Alaska SAR Demonstration (denoted by "demonstration" in the table): wind measurements, vessel detection, and storm monitoring. The remainder of this article will describe these products and the demonstration. Other applications listed in Table 1 are in a "research" status and are actively being investigated for development into practical techniques for CoastWatch. If successful, these will be added to the demonstration as resources permit.

ALASKA SAR DEMONSTRATION

Overview

A demonstration of near–real-time SAR applications in Alaska began in the fall of 1999, with an anticipated duration of at least 1 year. The areas of interest are coastal Alaska waters of the Bering, Beaufort, and Chukchi seas as well as the

Table 1. SAR applications of interest to CoastWatch.

Application	Status in NOAA
Coastal oceanographic	
Coastal ice analysis/forecasting	Preoperational
Vessel position detection for fishery surveillance/management	**Demonstration**
Ocean feature analysis (fronts, currents, eddies, etc.)	Development
Identification of natural and man-made oil slicks	Development
Internal wave measurements for mixed-layer depth	Research
Detection/mapping of algal blooms	Research
Iceberg detection/tracking	Potential
Wave measurements for maritime safety	Potential
Hydrologic	
Analysis of river ice jams and associated flooding	Preoperational
Lake ice analysis/forecasting	Preoperational
Mapping of coastal and river flooding	Research
Monitoring of glacier-dammed lakes	Potential
Meteorological	
Ocean surface wind measurements	**Demonstration**
Winter storm and hurricane studies	**Demonstration**
Geographic	
Detection of coastline changes	Potential
Mapping of wetland use/changes	Potential

northern Gulf of Alaska (42ºN–76ºN, 122ºW–155ºE). Goals for the demonstration are to (1) validate and test prototype SAR products that respond to critical needs not satisfied with present observational data in the Alaska region; (2) provide SAR imagery and derived products in near–real time via the Internet for trial use by operational agencies; and (3) familiarize operational agencies with SAR imagery data and products.

Users

Three major user groups are participating in the demonstration. The primary users of wind and storm image products are the Anchorage, Juneau, and Fairbanks NOAA/National Weather Service (NWS) forecast offices and the NWS Alaska Regional Office in Anchorage, including the Alaska River Forecast Office and the Alaska CoastWatch node. Collectively, these offices have three marine forecasters who issue 25 coastal forecasts 3 times a day. Their region of responsibility includes 54% of the U.S. coastline. Their mission, although focusing on protection of life and property, also includes aiding the economic stability of the country. It is anticipated that SAR imagery and products will provide valuable coastal wind data to a region with limited *in situ* marine measurement capability (there are only four U.S. meteorological buoys in Alaskan waters, one in the Bering Sea, one in the Gulf of Alaska, and two in Prince William Sound; and only four Coastal-Marine Automated Network meteorological stations exist to serve 50,000 km of coastline).

Alaska has a harsh marine environment, with ice hazards, severe storms, large waves, and dangers from superstructure icing. During the first 3 months of 1999, 11 people died and 14 more were seriously injured owing to severe weather conditions encountered by the snow crab fishery in the Bering Sea. SAR data are already being used by the National Ice Center and the NWS forecasters in Alaska to obtain ice information for Alaskan waters. In addition, the Alaska River Forecast Center has used SAR data for 3 years to monitor Alaskan river ice breakup in the spring.[3] Besides providing additional wind observations, SAR imagery should yield unique and valuable information on storms at sea, particularly polar mesoscale cyclones (also known as polar lows or arctic hurricanes; see Fig. 2). These storms can arise suddenly and intensify to hurricane-force winds with little or no warning from Alaska's sparse observation network.[4] In addition, overlying clouds often obscure these storms in conventional visible and infrared satellite cloud imagery. SAR data can provide unique, high-resolution information on the morphology of the storm at the ocean surface, including the location of the storm center and frontal regions.

The primary user for offshore vessel position data is the Coast Guard 17th District Office in Juneau, which is responsible for enforcing U.S. fishing regulations in U.S. waters, participating in enforcement of international agreements on the high seas, responding to oil spills, and rescuing those in peril at sea. The Coast Guard is particularly interested in ensuring that foreign fishing vessels are not trespassing into U.S. waters in the U.S./Russian Maritime Border region, monitoring Steller sea lion rookeries in the Aleutian Islands and illegal fishing in restricted waters around the rookeries, and monitoring illegal drift net fishing activities in international waters south of the Aleutian Islands.

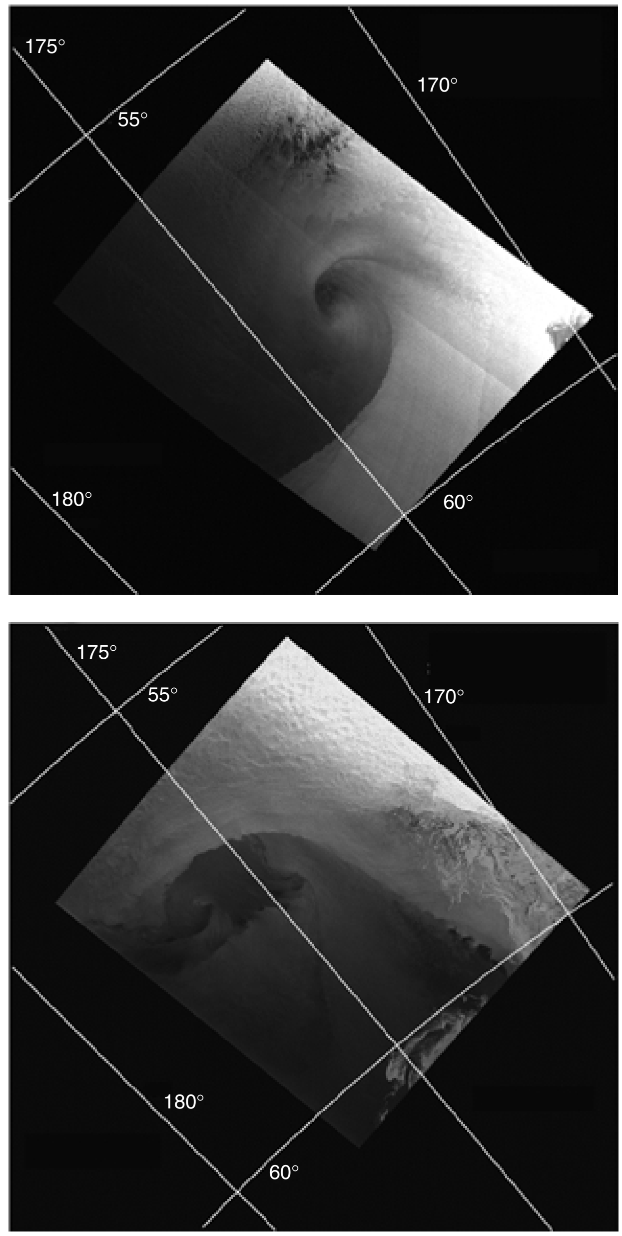

Figure 2. Two polar mesoscale cyclones as imaged by the ScanSAR wide B mode of the Radarsat SAR. Both storms are located in the same region of the Bering Sea, but are separated in time by 48 days (5 February and 25 March 1998). North is to the lower right corner (© Canadian Space Agency, 1998). (Figures prepared by Karen Friedman, Caelum Corp.)

With limited ship and aircraft resources and a vast region of responsibility, it is anticipated that SAR information on ship location and patterns of fishing activity will aid in the efficiency of search activities, in the monitoring of compliance when assets are not available in a particular region, and in the augmentation of legal case packages for prosecution of offenders. Imagery provided in preparation for the Alaska SAR Demonstration has shown vessel positions in relation to the U.S./Russian Maritime Border (Fig. 3) and vessels possibly engaged in illegal drift netting (still to be confirmed).

One question to be answered by the demonstration is the practicality of merging satellite-derived ship positions with ship identification and position information provided by the Vessel Monitoring System (VMS) scheduled for deployment during the next few years (see the article by Montgomery elsewhere in this issue). This system will require vessels participating in particular fisheries, such as the Atka mackerel fishery, to carry beacons that can be queried by the Coast Guard to monitor legal fishing activity. If queried at SAR satellite overpass times and paired with SAR-derived vessel positions, one should be able to tell if there are nonreporting vessels participating in the fishery.

The primary user of coastal vessel position data is the Alaska Department of Fish and Game (ADFG), which is responsible for managing fishing activities in Alaskan coastal waters in order to provide for maximum sustained yield. For example, ADFG manages the Pacific herring fishery for harvesting herring roe, which occurs between late April and early June, particularly in Togiak Bay within Bristol Bay. Herring are caught with purse seines and gill nets. Also, roe sacks are harvested from kelp by divers. The herring and roe are transferred to Japanese tramp freighters, which extract the roe and transport the catch to market in Japan. This fishery is highly regulated; the herring roe season is sometimes only open for 15 min every few days. Standard mode SAR data from Radarsat-1 and ERS-2 were used in the spring of 1998 and 1999 to get a synoptic view of herring roe fishery environmental conditions and vessel distribution.

Products and Algorithms

The initial demonstration system has three main products: (1) SAR imagery, (2) ocean surface wind measurement from SAR, and (3) ocean vessel position detection from SAR. Ancillary products are also provided to put the SAR imagery and derived products into the context of other available satellite, surface, and model environmental data. The primary source of SAR data is the Canadian Radarsat-1 satellite carrying a C-band (5.6-cm) SAR with horizontal transmit and receive polarization. The most common data modes used in the demonstration are ScanSAR wide B (450-km swath and 100–200-m resolution) and standard (100-km swath and 25-m resolution). Occasionally, the ERS-2 SAR (vertical transmit and receive polarization), with its 100-km swath and 25-m resolution, provides additional imagery when rapid repeat coverage is required.

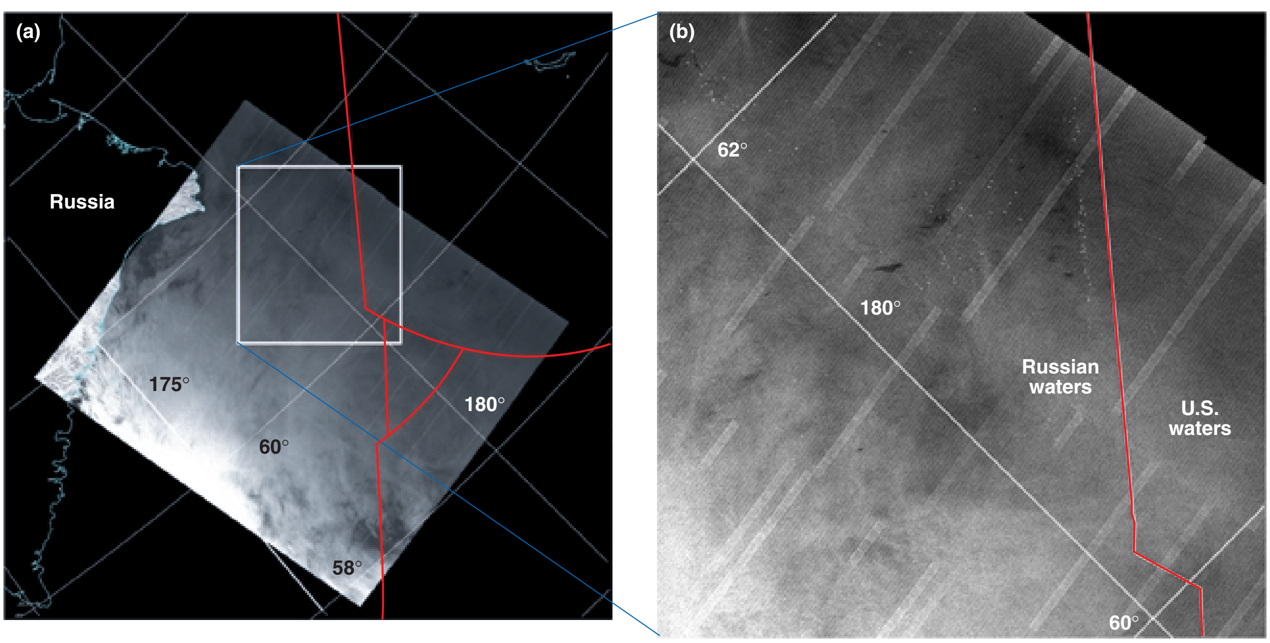

Figure 3. The U.S./Russian Maritime Border. (a) ScanSAR wide B image from 5 July 1999 at 0542 GMT near Cape Navarin, Russia, in the Bering Sea. The area in the white rectangle is enlarged in (b), which shows ships (white dots) aligned with the border engaged in the walleye pollack fishery (© Canadian Space Agency, 1999). (Figures prepared by Karen Friedman, Caelum Corp.)

SAR Imagery and Ancillary Products

During the Alaska SAR Demonstration, SAR imagery data are made available to users via an Internet-based image processing, analysis, and archiving system known as the WWW Image Processing Environment (WIPE) developed by the Applied Coherent Technology Corporation. The WIPE system ingests near–real-time SAR imagery and catalogues the data in a database for subsequent query by the end-user running an Internet browser on a PC or UNIX computer. The system allows the user to download or browse the SAR-derived products and ancillary data; do image processing and analysis; create data cubes of collocated image, vector, and point data; and output/download data cubes or selected individual data sets.

Table 2 lists the initial products to be delivered by WIPE. The user requests data for a particular time period over a particular area. The coverage of available products is presented on a map for the user to select for downloading or display. Selected data are displayed as black and white or color images. Latitude and longitude grid lines, coastlines, bathymetry, and terrain elevations can be shown with the image. SAR imagery can be zoomed to full resolution and overlaid with derived product graphics or ancillary data. WIPE supports a number of input and output formats and can output data in polar stereographic or simple cylindrical projections. WIPE can be programmed to deny access to SAR imagery while still allowing access to derived products for users who are not part of the U.S. government or are not approved Radarsat investigators. The SAR demonstration WIPE server resources allow up to four users to analyze data simultaneously without serious degradation in response time. This constraint is consistent with

Table 2. Alaska SAR Demonstration products.

Product	Source	WIPE data display	Download format (external to WIPE)
SAR imagery			
Radarsat	ASF via SAA	B/W image	Available from SAA
ERS-2	ASF via SAA	B/W image	Available from SAA
Ancillary data			
GOES visible and IR imagery	NESDIS	B/W image	Available from other sources
ERS-2 scatterometer wind vectors	NESDIS	Color wind barbs	Text file, GIF image
SSM/I wind speed	NESDIS	Color image	Text file, GIF image
14-km SST analysis	NESDIS	Color image	GIF image
Buoy observations (winds, SWH, air temp., SST, air pressure)	NDBC	Location, time, and values	Text file
Model analysis and forecast output (winds, SWH, air temp., SST, air pressure, dominant wave period and direction)	NCEP/ FNMOC	Color image for all parameters; color wind barbs for winds	GIF image
Model air–sea temp. difference analysis and forecast	APL	Color image	GIF image
Model inverse wave age analysis and forecast	APL	Color image	GIF image
SAR-derived products			
Vessel positions	ERIM	Symbols	Text file
Winds from SAR (vectors with 180° ambiguity)	ERIM	Color wind barbs	Text file
SAR wind imagery	APL	Color image; color wind barbs	Meta data file, validation file, GIF image

Notes: APL = The Johns Hopkins University Applied Physics Labararoty, ASF via SAA = Alaska SAR Facility via the NESDIS Satellite Active Archive, ERIM = Environmental Research Institute of Michigan International, Inc., FNMOC = Fleet Numerical Meteorology and Oceanography Center, GOES = Geostationary Operational Environmental Satellite, NCEP = National Centers for Environmental Prediction, NDBC = NOAA Data Buoy Center, SSM/I = Special Sensor Microwave/Imager, SWH = significant wave height.

the limited number of demonstration participants. Server resources can be expanded as more users are added.

SAR-Derived Ocean Surface Wind Measurements

Measurement of ocean surface winds from satellite scatterometer data is now quasi-operational. The routine availability of ERS-1/2 C-band and ADEOS Ku-band scatterometer data has fostered the development of mature algorithms for the derivation of wind speed and direction from such data. But SAR instruments also have the potential for wind measurement. Like scatterometers, a SAR instrument measures variations in radar backscatter from the wind-roughened ocean, variations which are a function of wind speed and direction. Unlike scatterometers, SAR instruments have only one azimuth viewing angle, so wind direction must be obtained using a technique that differs from the multiple-azimuth measurement algorithm used with modern scatterometers.

An independent estimate of local wind direction, either from model output or from another source, is required for accurate wind measurement. Under the right conditions, windrow patterns in the SAR data can themselves be used to infer wind direction with 180° ambiguity.[5] SAR wind measurements have the advantage of being at very high spatial resolution (in the absence of noise, down to 1 pixel; i.e., 25 to 100 m as opposed to the normal scatterometer resolution of 25 to 50 km) and can be made right up to the coast or in bays and estuaries without suffering from the land contamination evident in scatterometers and passive microwave radiometers. Two SAR wind products are being generated for the Alaska SAR Demonstration. Both will be evaluated and compared as to their utility to operational weather forecast and analysis activities.

SAR wind images. An experimental procedure has been developed by APL for estimating wind speed from Radarsat ScanSAR wide B and standard mode SAR imagery. The data are first calibrated to units of radar cross section using the calibration techniques provided by the Alaska SAR Facility (ASF), University of Alaska, Fairbanks, and then averaged to 1-km pixels. A modified scatterometer wind algorithm is then used to relate radar cross section to wind speed. The algorithm is the CMOD4, modified for the horizontal transmit, horizontal receive (HH) polarization of the Radarsat SAR (see the articles by Thompson and Beal as well as Monaldo, this issue). Accurate wind estimates from this algorithm require knowledge of the wind direction, the angle between the wind direction and the radar look direction, and the SAR incidence angle as well as accurate, normalized radar cross section measurements. In the preoperational wind procedure being developed, wind direction is obtained from a model wind analysis or forecast (on a 1° latitude/longitude grid), either from the Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC) or the NOAA National Centers for Environmental Prediction (NCEP). Wind directions from the model gridpoint analyses are interpolated to the SAR image pixels, and then SAR wind speed is calculated. The output is a high-resolution coastal wind speed map at a 1-km resolution (see Fig. 4).

SAR wind vectors. A second wind product has been developed by ERIM International, Inc., for the demonstration. In this algorithm, the wind direction is obtained from the SAR image itself when windrows or other wind-aligned features are present in the SAR image. Fast Fourier transforms are performed on sections of the image, and the direction of the wind is determined from the peak in the spectrum or the smear of energy in the spectrum in the crosswind direction.[5] The wind speed is determined with an algorithm similar to that used for the SAR wind images. Wind vectors over the ocean on a regular grid mesh with a spacing of approximately 32 km and 180° ambiguity in direction are the output of the algorithm.

Ocean Vessel Position Detection from SAR

Ships are often detected through visual examination of SAR imagery. They appear as bright targets with a contrast that depends on the background ocean backscatter. This contrast varies with wind speed, incidence angle, wave conditions, the presence of ocean features, and proximity to the coast. Because of the varying contrast, and the possibility that ocean features in some regions of an image can have a radar cross section as large as a ship return, a constant backscatter threshold often cannot be applied to the entire image to detect only ships. What is required is a point target detector.

This classic signal processing problem is often solved using a constant false alarm rate (CFAR) algorithm. A CFAR algorithm for ship detection has been developed by ERIM International, Inc., and has been incorporated in the Alaska SAR Demonstration. This algorithm detects ships by first generating a local estimate of the probability density function of the background ocean, then calculating a threshold such that there is a specified small probability (i.e., the false alarm rate) of finding a pixel above this threshold. Any pixel above the threshold is considered a ship.

In practice, a large "background" data box (e.g., 19×19 pixels) is defined for determining the background statistics and a small "signal" box (e.g., 3×3 pixels) at the center of the background box is used to locate targets. The samples within a midsized "background removal" box (e.g., 7×7 pixels, which is the size of the largest ship expected, also at the center of the background box) are not used when calculating the

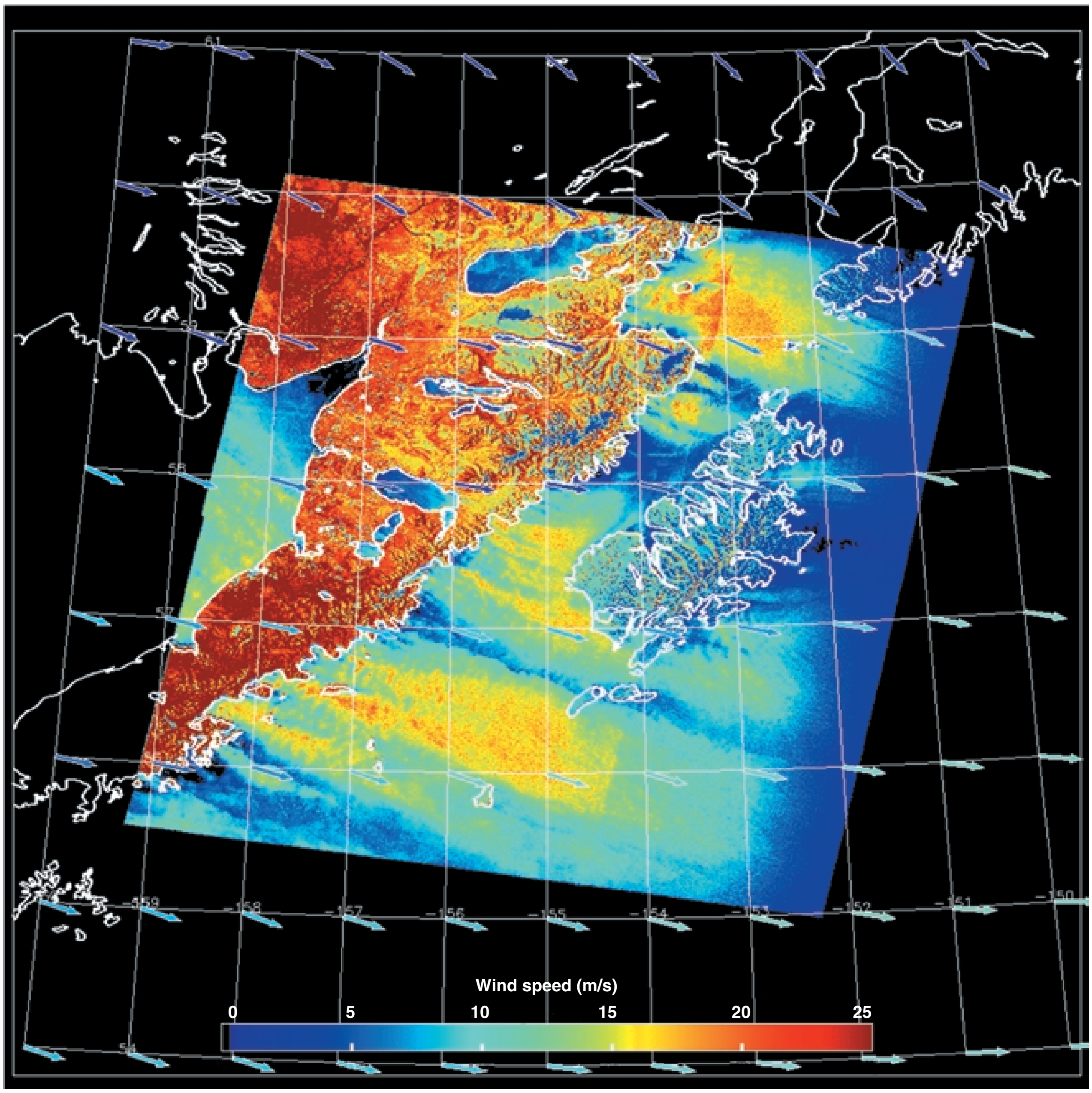

Figure 4. Wind field calculated from a Radarsat ScanSAR image over Cook Inlet on 24 September 1999 using the CMOD4 algorithm and an HH/VV polarization ratio of 0.6. The arrows are the model wind directions. (Image courtesy of Frank Monaldo, JHU/APL.)

statistics of the background box. The boxes are moved throughout the image to find all the ships. Since the local statistics are recalculated each time the boxes are moved, the threshold varies over the image. A land mask is employed to exclude land targets. Targets within 2 km of land are flagged since this region is susceptible to false alarms caused by satellite navigation errors or rocks, small islands, and mud flats not included in the land mask.

Figure 5a is a small section of a Radarsat ScanSAR wide B image in the Bering Sea. There are fishing vessels in the image, most probably engaged in the walleye pollack trawl fishery. Dark regions behind the bright ship point targets are presumed to be slicks resulting from release of fish oils during the processing of the catch and release of by-catch.[6] Figure 5b is the output of the CFAR algorithm showing the position of each detected ship.

Anticipated Products

If all goes well with the launch of the European Space Agency's Envisat satellite in November 2000, and if these data can be processed at the ASF, plans are

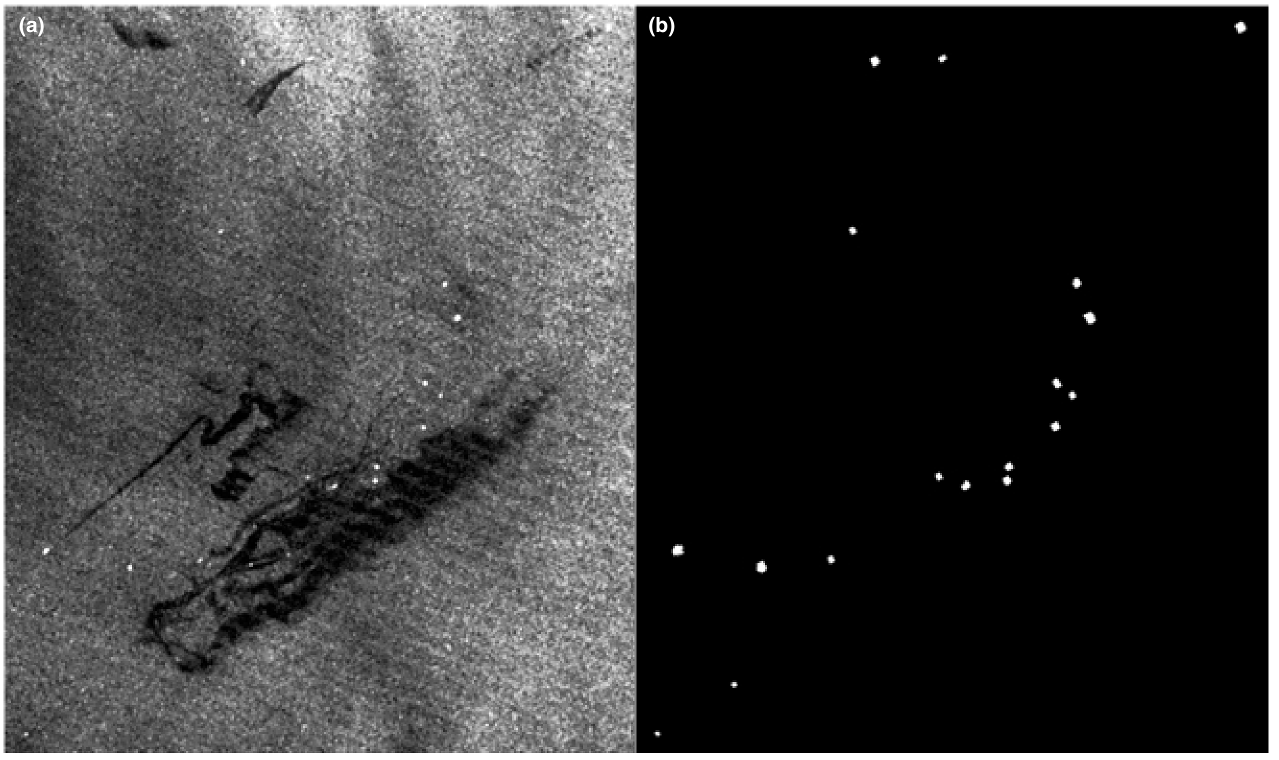

Figure 5. Image in the Bering Sea (a) showing vessels engaged in the walleye pollack fishery, with dark areas of water calmed by release of fish oils during processing of the catch (© Canadian Space Agency, 1997). Ships detected in (a) are shown by dots in (b) (courtesy of Christopher Wackerman, ERIM International, Inc.).

under way to add Envisat images to the Alaska SAR Demonstration. This will provide additional temporal coverage. Other possible products include an ice mask, Quickscat scatterometer winds, and an ocean feature and oil spill map.

Demonstration Data Flow

Figure 6 details the flow of data within the Alaska SAR Demonstration. In brief, the major data processing and communication activities are as follows.

1. SAR data reception and image processing: SAR data received at the ASF are processed from satellite instrument data into SAR imagery in near–real time (3–6 h). The images are then sent automatically via a dedicated T1 (1.544-Mbit/s) link to the NESDIS/SAA in Suitland, Maryland.

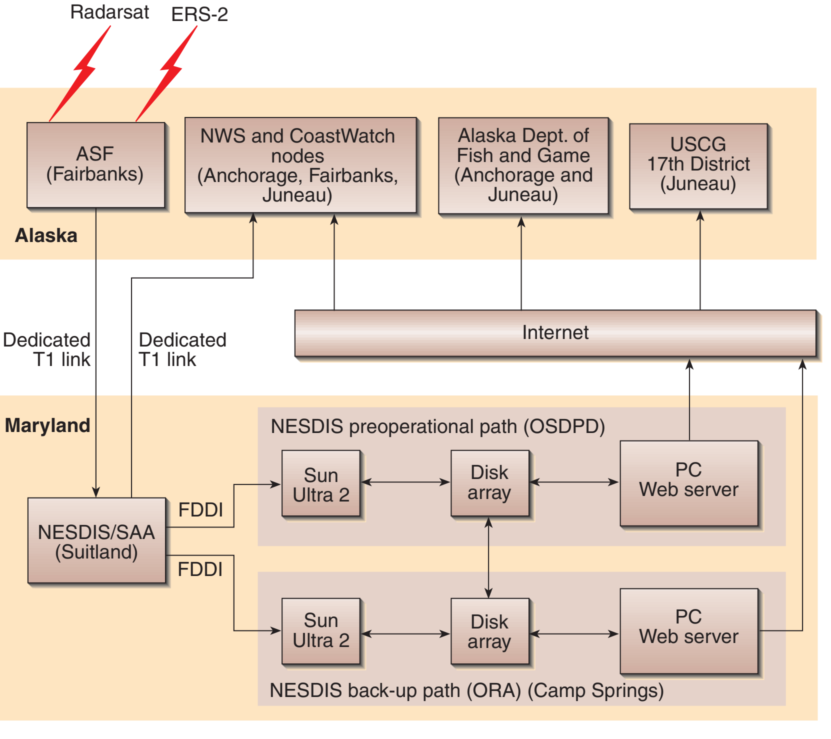

Figure 6. Alaska SAR Demonstration data flow (see text for brief description).

2. Satellite active archiving: Data are catalogued, stored online for 1 week, and then stored in a robotic tape system for 3 years. After cataloging, data are sent automatically to the NESDIS Office of Satellite Data Processing and Distribution (OSDPD) Sun Ultra 2 workstation in Camp Springs, Maryland; the NESDIS Office of Research and Applications (ORA) Sun Ultra 2 workstation in Camp Springs, Maryland; and the NWS forecast office Indigo 2 (Silicon Graphics, Inc.) workstation in Anchorage, Alaska. Data flows via a fiber-distributed data interface (FDDI) network (at 100 Mbit/s) from Suitland to Camp Springs. A dedicated T1 links Suitland to the NWS office in Anchorage.
3. Product processing: In the OSDPD facillities, the data are stored in a large disk array (234 GB) accessible to both the Sun Ultra 2 workstation and a PC running Windows NT. This disk array and a similar ORA disk array are both accessible by the OSDPD Sun, the ORA Sun, the OSDPD PC, and the ORA PC. The OSDPD Sun runs the software to calculate products, storing them in the disk array for access by WIPE.
4. Product and data user access: Data are provided to the user via Web browsers connected to WIPE running in the OSDPD PC.
5. System backup and validation: ORA has a Sun Ultra 2 workstation, a disk array, and a PC identical to the OSDPD platform. This system will serve as a backup for the OSDPD machine and in addition hosts the ERIM International, Inc., SAR tools software to be used for SAR algorithm development and testing. The machine will also be used for system development, testing, and validation work.

During the demonstration, wind products will be matched with buoy and model winds to monitor and measure SAR wind algorithm performance. Target detection algorithm performance will be assessed by comparing output with known U.S. Coast Guard and commercial vessel positions, and eventually with known positions of vessels participating in the VMS.

SUMMARY

The NOAA/NESDIS-sponsored Alaska SAR Demonstration began in the fall of 1999, providing near–real-time SAR-derived wind and vessel position products and SAR imagery to a small group of operational users in Alaska. SAR imagery and products are stored on a server and can be viewed over the Internet with a Web browser. The goal of this demonstration is to provide routine preoperational SAR products in near–real time for evaluation and validation.

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THE AUTHORS

WILLIAM G. PICHEL is a with the NOAA/NESDIS Office of Research and Applications in Camp Springs, MD. His e-mail address is wpichel@nesdis.noaa.gov.

PABLO CLEMENTE-COLÓN is affiliated with the NOAA/NESDIS Office of Research and Application in Camp Springs, MD. His e-mail address is pablo.Clemente-Colo@noaa.gov.