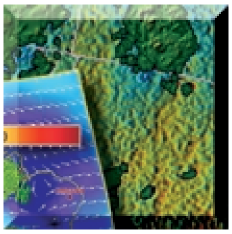

The Alaska SAR Demonstration and Near–Real-Time Synthetic Aperture Radar Winds

Frank Monaldo

Spaceborne synthetic aperture radar (SAR) imagery of the ocean surface reveals high-resolution patterns of wind speed and direction variations. These patterns offer the tantalizing prospect of measuring surface winds from space in coastal regions. It is precisely in coastal regions where high-resolution wind speeds are both necessary and particularly difficult to measure from space. One purpose of the Alaska SAR Demonstration effort is to demonstrate that SAR data can be processed into estimates of wind speed sufficiently quickly and accurately to be useful operationally. The second important goal is to define the circumstances under which SAR wind speed estimates are reliable and accurate. We describe the procedures for real-time production of SAR high-resolution wind speed estimates and provide examples of such imagery. (Keywords: Coastal winds, Real-time processing, Synthetic aperture radar.)

INTRODUCTION

The normalized radar cross section (σ^0) of the ocean surface depends on radar parameters such as frequency, polarization, and incidence angle. In addition, and most important for our application here, cross section depends on the wind speed and direction with respect to the radar look direction. As the surface becomes rougher on scales of the radar wavelength, the backscattered return grows larger. Since a synthetic aperture radar (SAR) can produce radar cross-sectional images at 100-m resolution over swaths of hundreds of kilometers, there is a tempting prospect of using SAR imagery from Radarsat and the European Remote Sensing (ERS-2) satellite to estimate wind speeds, particularly in coastal regions. This article focuses on the use of Radarsat SAR imagery as processed by the Alaskan SAR Facility (ASF).

In the winter of 1999–2000, we have an important opportunity to demonstrate real-time esitmation of high-resolution winds from Radarsat as part of the Alaska SAR Demonstration (see Pichel and Clemente-Colón, this issue). This demonstration will focus on the area 155°E to 122°W longitude and 42°N to 76°N latitude as shown in Fig. 1. Typically, over 12 wide swath SAR passes will be acquired in this region weekly. Figure 1 shows one typical pass crossing over Cook Inlet. As data are acquired by Radarsat, they will be downloaded to ASF located in Fairbanks, Alaska. ASF will then correlate the data to produce calibrated

Figure 1. The Alaska SAR Demonstration region. A sample wide swath SAR pass is shown covering part of the Gulf of Alaska and Cook Inlet. (Pass location information provided courtesy of Karen Friedman, National Oceanic and Atmospheric Administration, the National Environmental Satellite, Data, and Information Service.)

SAR images that will ultimately be turned into wind speed estimates. Before the operational use of SAR for high-resolution wind speed becomes a reality, several important issues need to be addressed.

Timely Acquisition

Because of the heavy computational requirements of producing SAR images, such imagery has typically been provided days after acquisition. One significant exception is SAR data routinely provided to the U.S. National Ice Center.[1] However, since ice measurements typically vary on timescales longer than the wind field, the timeliness requirements for operational wind speed estimates are more challenging. ASF has demonstrated the ability to produce wide swath SAR imagery (500 km wide) within a couple of hours after data acquisition.

Use of Ancillary Data

A SAR typically measures radar cross section at each point on the surface at one particular incidence angle and orientation with respect to the wind. Unfortunately, the relationship between cross section and wind speed is not unique. For any measured cross section there are a variety of combinations of wind speed and direction that will produce the same value of radar cross section. Spaceborne scatterometers resolve this ambiguity by measuring the surface cross section at a number of aspect angles and polarizations. However, scatterometer technology permits spatial resolutions of only 25–50 km, applicable more to the open ocean than to coastal areas.

This uniqueness problem can be resolved in SAR imagery if we are provided with an estimate of wind direction. Some have proposed using the spatial variation in the cross sections caused by windrows as a way to measure wind direction from the SAR imagery itself. Although such signatures definitely exist, they do not exist all the time. For our purposes here, we have chosen to use wind direction estimates from numerical forecast models. Nonetheless, there is nothing in the procedure presented here that precludes the possibility of using the SAR imagery itself to provide wind direction.

For an operational procedure to work there must be a ready source of model wind direction estimates. Thus far we have used data from the Naval Operational Global Atmospheric Prediction System (NOGAPS) provided by the U.S. Navy's Master Environmental Library (MEL). These data are on a 1° × 1° latitude–longitude grid. Current plans call for migrating to higher spatial resolution data from the U.S. National Center for Environmental Prediction.

The use of ancillary data involves questions of timeliness as well. Nowcasts of wind speed may not be available at the same time as the SAR imagery. For example, it is possible for the SAR data to be acquired at 1200 GMT (Greenwich Mean Time) and be made available at 1400 GMT, while the wind direction nowcast for 1200 GMT may still not be available. In such a case, it might be necessary to use the 12- or 24-h wind direction forecast for 1200 GMT. Obviously, the longer the forecast time, the less reliable the wind directions. We typically have used nowcasts of wind direction for non–real-time SAR wind speed estimates and 12-h forecasts for real-time estimates.

Geographic Registration

Rather than using cross-track and along-track coordinates natural to the SAR imaging process, it is most convenient for users if data are in rectilinear latitude and longitude coordinates. Although conceptually simple, such resampling can be computationally intensive.

Inference of Wind Speed

Even given timely SAR estimates of radar cross section and an estimate of wind direction, there still is the question of the optimum algorithm for retrieving wind speed from cross section. Considerable effort was expended to develop the CMOD4 algorithm wind speed-and-direction-to-cross-section relationship for the ERS-1 scatterometer and SAR. Despite significant efforts at validation, questions still remain about the applicability of the algorithm for wind speeds significantly above 20 m/s. Moreover, this algorithm is applicable only to C-band vertical (VV) polarization. In this project, we are using horizontal (HH) polarization data from the Radarsat SAR. Uncertainty in the CMOD4 algorithm is compounded by difficulty in specifying the polarization ratio.

If $\sigma^0_V(U, \phi, \theta)$ represents the radar cross section as a function of wind speed (U), aspect angle with respect to the wind (ϕ), and incidence angle (θ), then the corresponding radar cross section at horizontal polarization can be expressed as

$$\sigma_H^0 = \sigma_V^0(U,\phi,\theta)\frac{(1+\alpha\tan^2\theta)^2}{(1+2\tan^2\theta)^2},$$

where α is a parameter that has been empirically estimated at 0.6.[2–4] (See also Thompson and Beal, this issue.) Wind speed retrievals from a SAR will still be limited by confidence in both the CMOD4 algorithm and the vertical-to-horizontal polarization ratio.

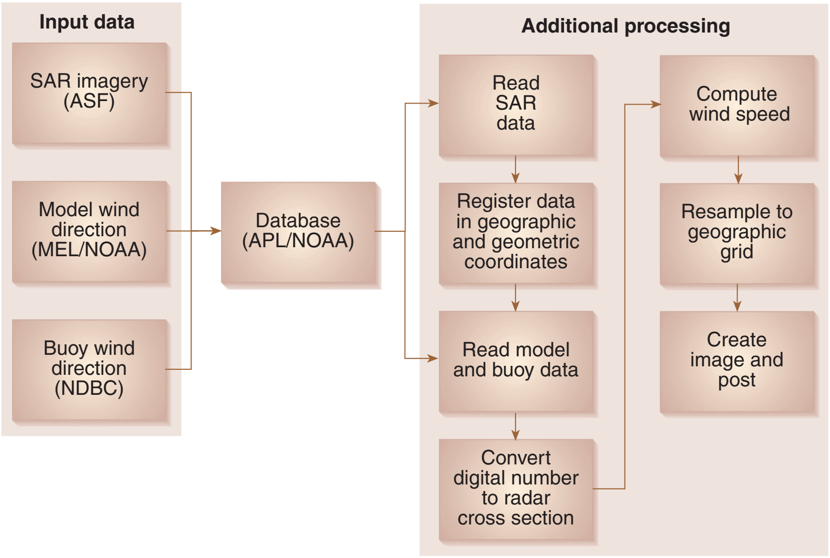

Figure 2. Diagram of data flow. (ASF = Alaska SAR Facility; MEL = Master Environmental Library [Navy]; NDBC = NOAA National Data Buoy Center; NOAA = National Oceanic and Atmospheric Administration.)

Validation

The issue of the appropriate wind speed algorithm dovetails into the question of validation. Wind speed measurements from buoys are encumbered by their own set of problems. These problems include sheltering in high sea states and the fact that the buoys make temporal averages of wind speed while spaceborne measurements average over space. Nonetheless, space-borne measurements have been traditionally validated against buoy measurements. To facilitate such comparisons, APL routinely downloads buoy data from the National Data Buoy Center (NDBC) and archives these data for comparison. The East Coast of the United States is heavily instrumented, so it is possible to make systemic comparisons between buoy and SAR wind speed estimates. In other areas, such as the Gulf of Alaska, many fewer such buoy comparisons are available.

Delivery of Wind Speed Estimates

The final challenge in providing SAR wind speed estimates operationally is making data available to potential users. We anticipate the use of two wind speed data products. The first would be either a binary or an ASCII-formatted file of wind speed arranged in a longitude–latitude array. The second output would be a pseudo-colored image of wind speed in GIF or other popular image display format.

DATA FLOW AND EXAMPLE

Figure 2 is a diagram of the data flow from SAR imagery to wind speed estimates. The elements of the processing roughly correspond to the challenges listed in the previous section. The primary input is ASF quick-look processed SAR imagery that is transmitted to APL and the National Oceanic and Atmospheric Administration (NOAA) for further processing. It may very well turn out that data transmission times, rather than SAR processing times, are a "rate-determining" step of the data flow. In such a case, it may ultimately prove prudent to carry out the steps labeled "Additional processing" in Fig. 2 near the same location as the SAR image correlation. During the symposium on emerging coastal and marine applications of wide swath SAR, we demonstrated that it is possible to produce a wind speed image within 5 h of SAR data acquisition. For this test case, the time from data acquisition to the time data started to flow to APL was about 2.5 h. The actual conversion to wind speed and resampling to geographic coordinates (the "Additional processing" box in Fig. 2) took 45 min. The remaining time was used in data transmission over the Internet from Alaska to Maryland on a business afternoon.

Currently, model wind speed and direction data are sent automatically to APL by MEL daily. In addition, we receive estimates of atmospheric pressure, air temperature, water temperature, ocean significant wave height, wave period, and dominant wave direction. The relationship between wind speed and radar cross section may depend on atmospheric stability. The additional information from MEL was obtained in case it might prove useful in the wind speed retrieval.

NDBC buoy data are available on the World Wide Web[5] and are downloaded regularly. All the data are stored in a database so that the data can be retrieved as needed.

The first step in converting SAR imagery to wind speed is to read the data and block average the data down to a convenient size. Typically we take wide swath SAR imagery in 100-m samples and average 4 × 4 pixels to generate imagery sampled at 400 m. Figure 3 is an example of an image covering the Gulf of Alaska. Here, the brightness is proportional to the digital value in the image, which in turn is proportional to SAR image amplitude.

The next step is to geographically register the imagery. ASF image data are generally provided in the polar stereographic projection. As such, there is a very specific relationship between horizontal and vertical pixel number and latitude and longitude. For convenience we perform the conversion of pixel position to latitude–longitude location for 100 points in the image sampled in a 10 × 10 grid. We then use a two-dimensional polynomial to fit the horizontal and vertical pixel counts to latitude and longitude and vice versa. Thus, for each image, we generate a computationally efficient means of going from image pixel position to the corresponding geographic position and vice versa.

From the model wind velocity data, we extract wind direction estimates. Using a bilinear interpolation scheme, we compute wind direction for every pixel in the SAR image. At each pixel in the image, we use the calibration information in the leader file that accompanies the data file to convert the digital value to radar cross section. The radar cross section is proportional to the square of the digital number in the image. The leader file provides the appropriate scaling coefficients.

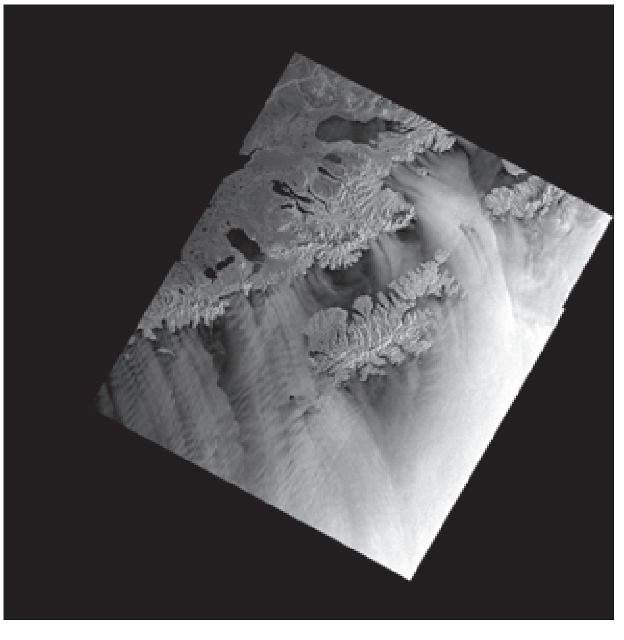

Figure 3. Sample image near Cook Inlet and Kodiak Island as processed by ASF. The imagery is in a polar stereographic projection. The intensity of the image is proportional to the byte value. The byte value, in turn, is proportional to image amplitude. This image was acquired on 6 October 1998 at 1637:44 GMT. The image center is 153.9°W, 57.6°N. (© Canadian Space Agency.)

For wide swath SAR imagery that was correlated before data were calibrated, we used nominal calibration coefficients obtained by comparison of image digital values with buoy wind speed data.[5] At this point in the process, we have a wind direction and a radar cross section for each element of the image. The CMOD4 algorithm and the polarization ratio give us a relationship among wind speed and direction, radar aspect angle, radar incidence angle, and radar cross section. We used these relationships to produce a lookup table to infer a wind speed from the cross-sectional and direction information. These wind speed data are then resampled onto a rectilinear longitude–latitude grid and used to generate a wind speed data file and pseudo-color high-resolution wind speed image.

Figure 4 represents different levels of processing. For the color-coded arrows in Fig. 4a, the colors indicate the wind speed from the NOGAPS model, and the arrow direction indicates wind direction.

Figure 4b shows the same wind image resampled to rectilinear latitude and longitude coordinates. The NOGAPS wind speeds are also displayed as well as a high-resolution coastline. The correspondence between this coastline and land edges in the SAR image confirms the accuracy of the latitude–longitude locations and transformations.

Figure 5 is an enlargement of the wind speed image from Fig. 4. It reveals the additional information derived from having high-resolution wind speed estimates. The image shows wind speed in the immediate vicinity of Cook Inlet (see Fig. 1). Of particular interest are the jets of wind apparently funneling through local topography and wind shadows behind the Barren Islands between Kenai Peninsula and Kodiak Island. Wind speed changes by more than 10 m/s in short distances. These are features that would not be detectable by conventional scatterometers and a passive microwave system such as the Special Sensor Microwave Imager radiometers on Defense Meteorological Satellite Program satellites with their 25- to 50-km resolutions.

CONCLUSION

We have been able to demonstrate that realistic high-resolution wind fields can be retrieved from calibrated wide swath SAR imagery. The full process takes about 5 h, a good portion of which is the transmission time from ASF to APL.

This retrieval is currently based on inferring wind speed from the radar cross-sectional measurements and a wind direction from model wind fields. Calibration is crucial in this application. Calibration offsets as small as 1 dB can cause significant changes in the wind speed retrieval.

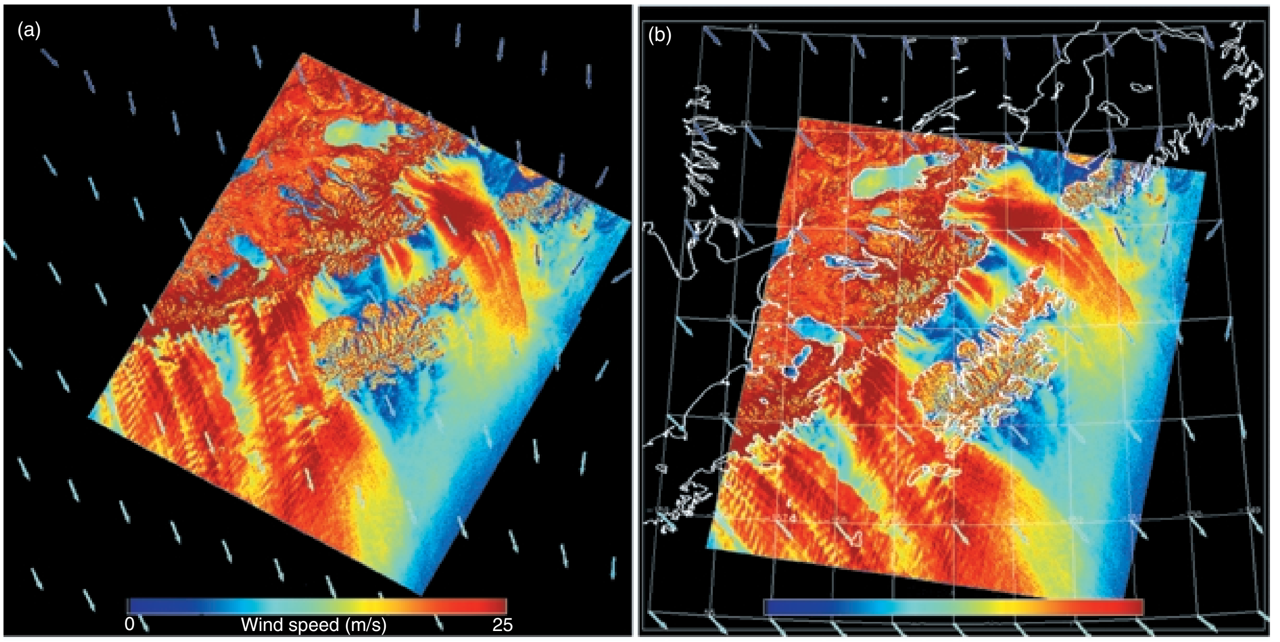

Figure 4. (a) A pseudo-color wind speed image in the original polar stereographic coordinates of the image. The arrows are color-coded NOGAPS model winds. (b) The same data resampled into rectilinear latitude and longitude. The color bar is the same as that in (a).

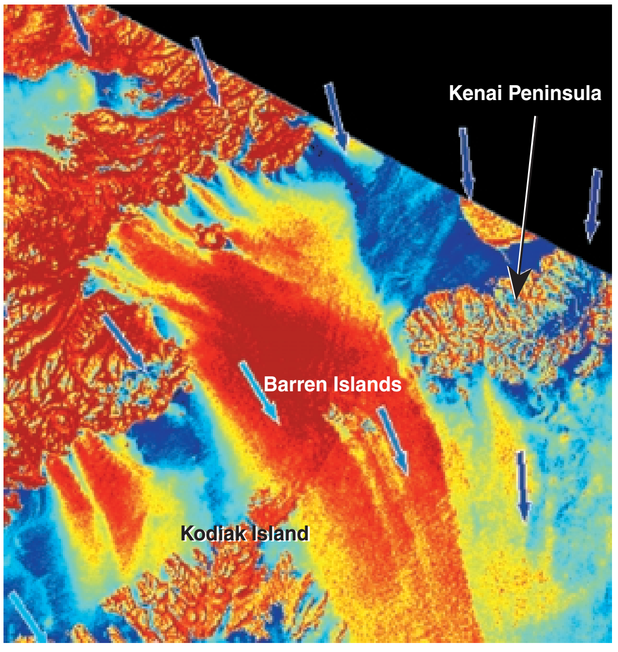

Figure 5. Enlargement of the region between Kodiak Island and Kenai Peninsula. Note the high wind speed jets funneling through the topography and the wind shadowing downwind of the islands.

Important issues for future work include (1) addressing data transmission times, (2) using higher-resolution wind speed models to obtain better *a priori* estimates of wind direction, (3) exploring the use of SAR imagery itself to extract wind direction, (4) validating the CMOD4 wind speed algorithm when used in conjunction with a polarization ratio, and (5) confirming the wide swath SAR calibration accuracy.

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