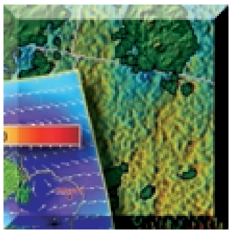

The Role of Wide Swath SAR in High-Latitude Coastal Management

Richard B. Olsen and Terje Wahl

Monitoring dynamic ocean and coastal processes at high latitudes with polar-orbiting synthetic aperture radar (SAR) systems is much easier than over other regions. The confluence of satellite swaths provides relatively frequent coverage, especially with the wide swath modes of satellites such as Radarsat-1 and Envisat. Norway is responsible for managing economic zones that stretch from 56 to 82°N, and has taken advantage of this favorable geography. The result to date is the establishment of operational services for fisheries monitoring in the Barents Sea and around Jan Mayen Island in the Greenland Sea, and for oil spill monitoring along the Norwegian coast and in the North Sea. Both programs make significant use of spaceborne SAR systems. (Keywords: Oil spills, SAR, Satellite oceanography, Ship detection.)

INTRODUCTION

Norway manages exclusive economic and fisheries zones of 2 million km^2, which is 6 times the size of its mainland areas (Fig. 1). The coastline is also very long and spans 13° latitude, facing some of the harshest weather conditions in the Northern Hemisphere. The location and the geography present extraordinary challenges to maintaining effective marine forecasting, resource management, and sovereignty rights in these waters.

In the 1980s, a cost-benefit analysis concluded that the cost of patrolling waters under Norwegian jurisdiction could be cut significantly by using radar satellites.[1] On the basis of this finding, Norway made a decision to invest in a national infrastructure specifically designed to support maritime observations using spaceborne synthetic aperture radar (SAR). By 1992, images were being distributed from Tromsø Satellite Station to Trondheim, Bergen, and Oslo within 100 min of reception. The advantage of being at high latitudes is evident for polar-orbiting platforms owing to the confluence of orbit tracks near the poles. For example, relative to equatorial waters, SAR coverage is 1.2 times as frequent for the Mediterranean Sea, 2.0 times for the North Sea, 3.0 times for the Norwegian Sea, and 4.5 times for the Barents Sea.

Although satellites cannot replace conventional platforms such as aircraft and ships entirely, it was demonstrated that satellite observations represent a tool for carrying out patrols more efficiently. Two areas of interest were given high priority: oil pollution and fisheries monitoring.

The European Remote Sensing satellites, ERS-1 and ERS-2, proved to be limited in ability to observe

Figure 1. Ocean and coastal areas under Norwegian jurisdiction: Norwegian economic zone, Jan Mayen, and the Svalbard fisheries protection zone. The gray zone is claimed by both Norway and Russia.

vessels because of the imaging geometry. Conversely, Radarsat-1 exceeded prelaunch predictions in its capability to observe both vessels and oil slicks. Both the oil spill and the fisheries monitoring programs have now changed from demonstration to operational status. Observations of potential oil slicks are reported by Tromsø Satellite Station to the patrol aircraft that regularly fly over the Norwegian coast. The aircraft can, if required, be redirected during flight to investigate suspicious slicks on the ocean.

Radarsat-1 data, primarily the ScanSAR narrow-far mode, are used to plan P3 flights to the more remote areas of Norwegian jurisdiction, particularly Jan Mayen Island. Maritime patrol aircraft fly routinely in the northern areas and monitor the fishing activity on behalf of the Norwegian Ministry of Fisheries. Radarsat-1 data are used to determine the general location of the fishing fleets and to decide if a patrol flight is necessary. An example is shown in Fig. 2, from the so-called "Loop Hole" in the Barents Sea, where foreign trawlers are located along the boundary line of the Norwegian 200-nmi (370-km) limit.

Radarsat-1 data acquisitions are planned on the basis of marine forecasts and predicted coverage. The ScanSAR narrow-far mode, with an incidence angle range of 31 to 46°, is the mode of choice, although the near mode (incidence angles of 20 to 39°) is sometimes chosen if it is the only option for coverage in time for a flight decision. Once the images have been acquired, they are analyzed to determine the presence of vessels. Vessel positions are then reported to the northern headquarters together with estimates of minimum detectable vessel size. The minimum detection sizes are based on weather predictions and the viewing geometry, using the method published by Vachon et al.[2]

The success of using Radarsat-1 led the Norwegian Defense Research Establishment to make a preliminary evaluation of the European Envisat, scheduled for launch in 2000. Envisat will carry advanced synthetic aperture radar (ASAR), together with several other payload instruments. ASAR will operate in five modes: image, alternating polarization, wide swath, global monitoring, and wave.[3] We next make some predictions for the use of its wide mode for ocean and coastal monitoring.

CONTRIBUTIONS OF WIDE SWATH SAR

The main contributions that wide swath SAR can make toward ocean and coastal monitoring are synoptic observations of meteorological and oceanographic

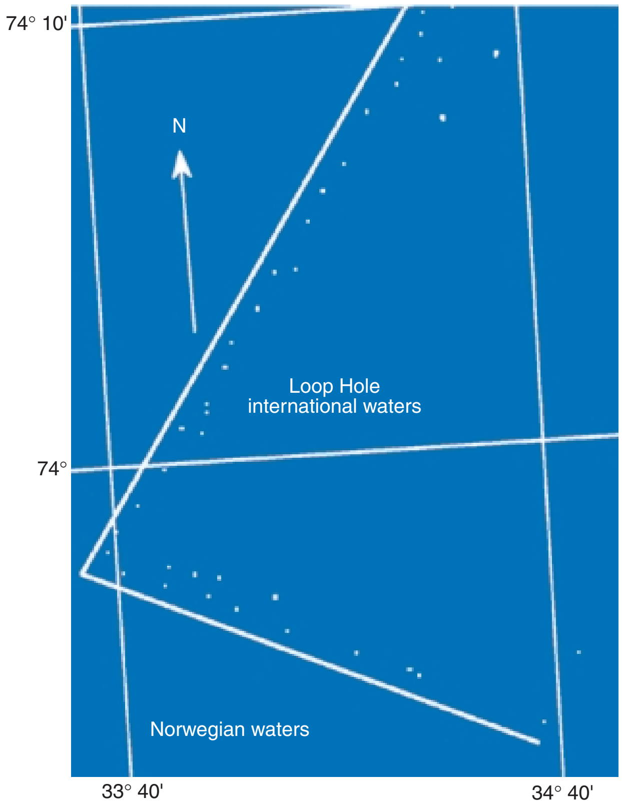

Figure 2. Radarsat-1 ScanSAR narrow-far image, 28 August 1996, showing foreign trawlers along the "Loop Hole" boundary. (© Canadian Space Agency.)

phenomena and wide area surveillance for monitoring vessel traffic, fisheries, and oil pollution.

Synoptic Observations

An important advantage of the wide swaths of Radarsat-1 and Envisat are that they cover areas that capture the scale of weather and oceanic systems: polar lows, eddies, and frontal features in the atmosphere and upper ocean. The Envisat global monitoring mode should supply useful data for meteorological applications, providing good coverage with relatively low data volumes.

SAR images reveal many meteorological phenomena not currently captured by other observational methods or models (e.g., Fig. 3). Even if they cannot be used in a real-time sense, they can contribute to understanding phenomena that may be related to certain meteorological situations.

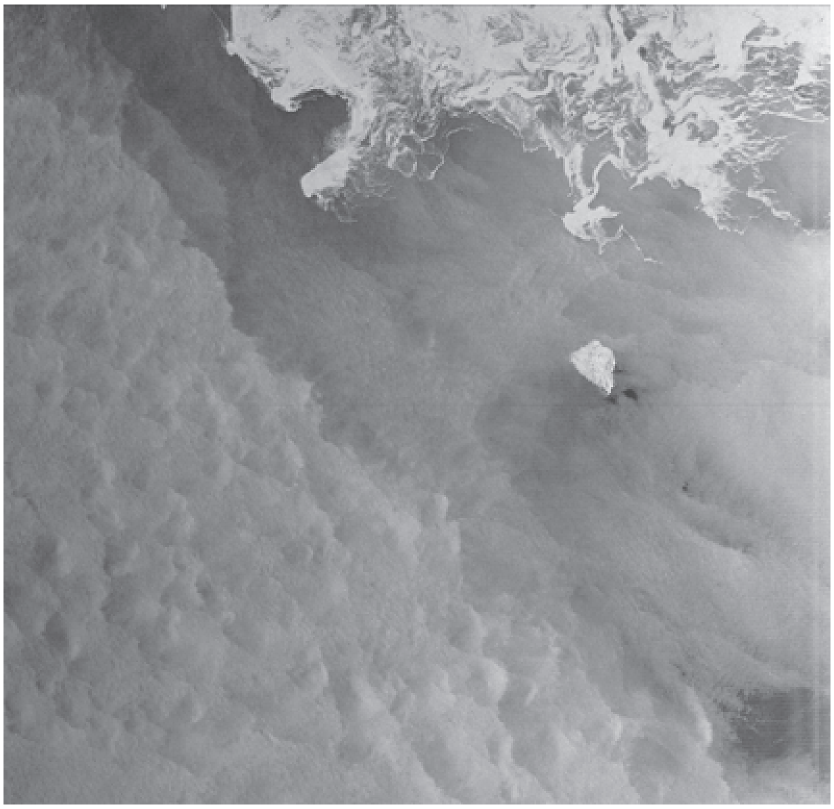

Figure 3. Image of a cold front near Bear Island, Barents Sea, obtained by Radarsat ScanSAR narrow-far mode. (© Canadian Space Agency.)

Typical eddy sizes along the Norwegian coast are of the order of 50 to 100 km. To properly understand the dynamics of a given observation, wide swath coverage is crucial to setting features in context. Similarly, effects of topography become much more apparent when the swath covers land a few tens of kilometers inland as well as the near-shore waters. The major front in Fig. 4 is hard to interpret without this contextual information. Although probably of atmospheric origin, it could be related to a topographic influence or a synoptic pattern, or it could represent a change in stability in the boundary layer due to a gradient in sea surface temperature.

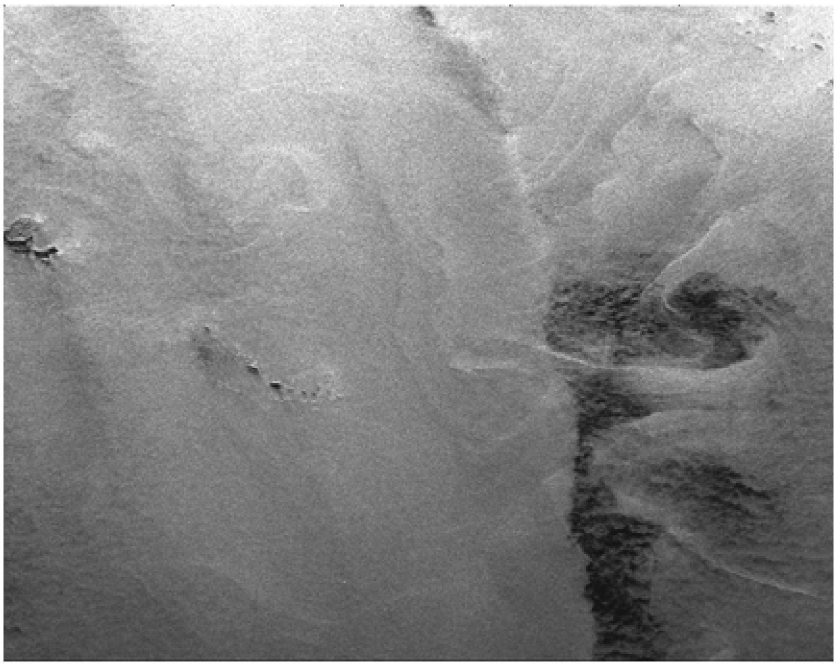

Figure 4. Image of frontal features in outer Vestfjorden, northern Norway, obtained by ERS-2. (© European Space Agency.)

We have observed many interesting features in coastal waters during high wind and sea-state conditions. This observation, combined with the level of detail found in the imagery, indicates that SAR is potentially a useful and reliable tool for providing information on local circulation patterns. The utility can be increased by improving our understanding of the mechanisms that generate observable signatures in SAR images, which must be done to enable quantitative information to be extracted from SAR data. We believe that wide swath coverage will improve spatial and temporal coverage and provide variations in incidence angle that will help unravel some of the ambiguities currently encountered in the data.

A possible disadvantage of the wide swath mode is lack of resolution to support certain analysis methods. The resolution will probably not support spectral methods for wind and wave analysis or even detailed analysis of oceanic front structures. Radarsat-1 ScanSAR narrow (50-m resolution) may be somewhat better than Envisat (150-m resolution), although azimuth cutoff effects, in reality, often degrade the resolution to values above 100 m.

Fisheries Monitoring

The key areas of interest for satellite SAR monitoring are those areas around Jan Mayen, the Barents Sea, and the protection zone around the Svalbard Islands. Fishing in these waters requires large vessels, with typical lengths of 30 to 80 m. To make some predictions for the Envisat wide swath for detecting fishing vessels, we use Vachon's[2] modified version of Skolnik's relationship to estimate the relationship between the radar cross section of a typical vessel σ_{ship} and vessel length L:

$$L = \left(\frac{\sigma_{ship}}{0.08 \cdot R(\theta)} \right)^{3/7} \; ; \; R(\theta) = 0.78 + 0.11\theta . \qquad (1)$$

Here, θ is the radar incidence angle, and $R(\theta)$ is an incidence angle–dependent term that was determined empirically in Ref. 2. A threshold T above the mean ocean backscatter σ_0 is used to determine σ_{ship}^{min}:

$$\sigma_{ship}^{min} = \rho_r \rho_a 10^{(\sigma_0 + T)/10} , \qquad (2)$$

where ρ_r and ρ_a are the range and azimuth resolutions, respectively. The ocean backscatter is calculated for a C-band radar transmitting and receiving vertically polarized signals (VV) using the empirical C-band modulation model CMOD4.[4] The estimates were converted to horizontally polarized (HH) transmitted and received data using polarization ratios from Unal et al.[5] The threshold is determined using a K distribution[2] for ocean clutter in a multilook SAR image with an order parameter of 4. The constant false alarm rate was set to 0.005. This approach should work well for low-resolution, wide swath images as opposed to images at higher resolution, particularly at high wind speeds, that contain considerable texture. For such images, higher-order statistics should be considered.

The results are summarized in Table 1, showing that even under ideal conditions, the inner swaths (1 and 2) will miss many of these vessels. The outer swaths (3–5) should perform well, however, both for VV- and HH-polarized data. Although likely not practical for Envisat operations, a vessel detection wide mode could be tailored by using cross-polarized reception for the inner beam, which would bring the ocean clutter down to gain around 15 to 20 dB of margin between the ocean and vessel backscatter. For higher incidence angles, this margin gain is eventually overcome by noise floor restrictions.

Oil Spill Detection

The space-based part of the Norwegian oil spill monitoring program primarily uses ERS imagery. Besides cost considerations, the ERS VV-polarized data provide improved contrast for oil slick detection compared to HH data from Radarsat-1. With Envisat wide swath data available, coverage will be much improved. To recommend the Envisat modes that would be most suitable for slick detection, we base our evaluation on a contrast requirement of −2 to −3 dB[6] for labeling features as potential oil slicks. This means that ocean backscatter should be at least 3 dB above the noise floor to support slick discrimination. Algorithms for slick discrimination use several parameters (including texture) that require signal levels well above the noise floor. With enough margin here, typical slicks exhibit backscatter suppressions around 5 to 15 dB. Figure 5 illustrates ocean backscatter for 5 and 20 m/s winds when the SAR is looking 90° relative to the wind direction (crosswind). When the SAR looks up or downwind, the signal levels will be higher. The estimated noise floor is about 4 dB below the expected low-wind backscatter for VV-polarized data at the outer edge of the swath, while HH-polarized data will be around the expected noise floor. We conclude, therefore, that the VV-polarized wide swath data will be the best option for monitoring slicks and should give a 400-km wide swath for this purpose.

CONCLUSIONS

Wide swath SAR is proving to be a useful tool for efficiently monitoring high-latitude ocean areas. Envisat will be a very good satellite for oil spill monitoring. The Radarsat-1 ScanSAR narrow-far mode provides adequate spatial resolution for monitoring fishing activity, even in high wind and sea-state conditions. Envisat's wide swath is not as well suited for this application, although a subset of it (3–5, see Table 1) can provide some adequate data.

The frequency of coverage provided by wide swath SAR instruments presents a good opportunity to study events that evolve at synoptic time scales at high latitudes. The wide area coverage enables observations to be made of weather systems and ocean circulation patterns at synoptic scales, which is a significant advantage over narrow swath modes.

Table 1. Predicted Envisat wide swath minimum length of detected vessels.

Radar signal	Subswath	Incidence angle (deg)	Upwind/crosswind minimum vessel length (m) detectable 5 m/s	10 m/s	20 m/s
VV[a]	1	18–26	178/155	219/189	312/225
	2	25–31	73/58	104/74	167/110
	3	30–36	51/38	77/51	132/85
	4	35–39	39/28	61/38	109/69
	5	38–42	32/23	52/31	97/61
HH[b]	1	18–26	166/144	208/180	297/214
	2	25–31	58/46	81/58	126/83
	3	30–36	37/28	54/36	89/57
	4	35–39	26/19	40/25	69/43
	5	38–42	20/15	32/19	57/36

[a]VV refers to radar signals that are vertically polarized when transmitted and received.
[b]HH refers to radar signals that are horizontally polarized when transmitted and received.

Another advantage of wide swath SAR at higher latitudes is that over a period of a few days, several opportunities exist to cover a particular area at different incidence angles. This incidence angle diversity allows tailoring of the observations to specific applications requiring high or low sea clutter levels, providing, for example, ship observations at large incidence angles or ocean surface feature observations at steeper angles.

As our understanding of ocean imaging mechanisms increases, more sophisticated algorithms for reducing the data to geophysical parameters are emerging. Some of these algorithms require access to details of the acquisition and SAR correlation processes. Some also require access to the data in other forms than the traditional multilook detected image. It is important to maintain a dialogue with commercial operators to ensure that the ground segments do not become closed systems that prevent access to such data.

The progress made in implementing operational monitoring programs also benefits research activities by providing a large set of images. Examples of images have been shown here that were collected as part of routine monitoring activities and will help point out new directions for future research.

The number of planned SAR missions is growing. A trend has developed toward commercialization as the technology matures. Many of the future satellites will, therefore, be owned and operated by commercial interests. Market analyses are driving the commercial entities toward terrestrial markets where commercial customers are more readily identified. These markets' requirements are tending toward high resolution and a shift to X band. Large area coverage is not necessarily a high priority. The ocean applications community must work closely with the commercial consortia to ensure that some of these missions will meet requirements specific to marine applications. In this context, wide swath data are essential.

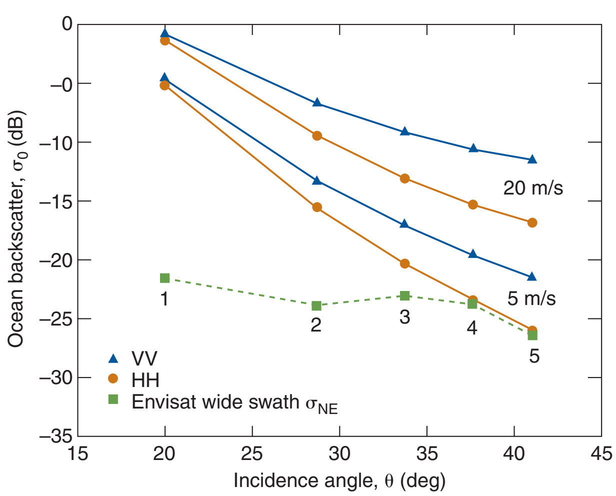

Figure 5. Ocean backscatter compared with the ASAR wide mode noise floor. σ_{NE} is the noise-equivalent σ_0 or noise floor.

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