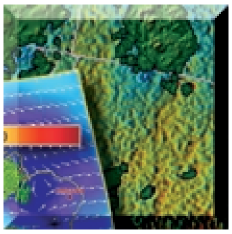

International Fisheries Enforcement Management Using Wide Swath SAR

Donald R. Montgomery

The application of wide swath synthetic aperture radar (SAR) for surveillance of commercial fishing grounds can aid in the detection of illegal fishing activities and provide more efficient use of limited aircraft or patrol craft resources. Many nations have vast economic enterprise zones that cannot be monitored for fishing activities with the available patrol resources. This is particularly true for small Pacific Island nations, whose resources preclude any effective monitoring methods. With wide swath SAR, large ocean areas can be monitored on frequent revisit schedules, thus allowing detected ships to be observed and identified by patrols that are vectored on these targets from cuing derived from the SAR information. (Keywords: Fisheries enforcement, Synthetic aperture radar, Vessel monitoring.)

ENFORCEMENT ISSUES

Over the past three decades, fishing harvests have risen by almost 30 million metric tons. With this expansion has come several undesirable consequences. The number of overexploited stocks has more than doubled—there were 51 documented in 1989.[1] Over half of the overexploited stocks are in the Atlantic Ocean, including 11 major stock groups in the central eastern Atlantic and 8 in the southeastern Atlantic. Whereas there are fewer overfished major stocks in the Pacific than in the Atlantic, this situation is rapidly changing, particularly in the North Pacific and Bering Sea.

Donut Hole Region

A unique situation exists in the Bering Sea where a large groundfish resource occupies the shelf and slope waters within the exclusive economic zone (EEZ) of both the United States and Russia. Centered between these national jurisdictions is a segment of international water, referred to as the Donut Hole, where foreign vessels once operated legally and forayed into adjacent slope and shelf waters to quickly harvest large quantities of groundfish before retreating back to the Donut Hole. Today, there is a moratorium that bans all fishing in the Donut Hole region, making close monitoring of the region an essential enforcement priority. More recently, it has been determined that foreign vessels fishing along the Convention Line (maritime boundary between Russia and the United States) are crossing the line to fish illegally in U.S. waters. In addition to harvesting a variety of fish species, these vessels are catching juvenile pollack during their westward migration from spawning grounds along the Aleutian chain, thus being removed from the stock before reaching maturity as a catchable resource.

A number of factors contribute to the overfishing and reduction in major fish stocks: management methods, political needs, and more importantly, a lack of effective fisheries surveillance methods and enforcement action. Often, legal commercial fishing operations exceed their allocated harvest quotas, and frequently there is significant wasted by-catch. In the United States, the Fisheries Observer Program, which places National Oceanic and Atmospheric Administration (NOAA)/National Marine Fisheries Service employees onboard commercial fishing vessels to monitor fish catch, helps reduce the impact of these overfishing activities for some fish stocks. Significant overfishing is also perpetrated by vessels from one nation encroaching illegally into the EEZ boundaries of another nation. More disturbing is the fact that rogue vessels harvest species in prohibited areas or during closed seasons with little fear of being detected, much less interdicted.

Use of Pelagic Drift Nets

Despite United Nations Resolution 46/215, which banned the use of large-scale pelagic drift nets on the high seas, there continues to be widespread illegal drift net fishing in the Pacific and Atlantic Oceans and in the Mediterranean Sea. For example, in the North Pacific region, where the use of large-scale drift nets for squid and other species is banned, illegal drift net fishing continues. Here, large numbers of salmon from the United States are intercepted, causing decreased salmon returns to the already-damaged West Coast stocks. A similar problem exists in the western Bering Sea, where legally licensed drift net fishing for salmon in Russian waters often exists, again harvesting U.S.-spawned salmon to further deplete the dwindling stocks.

It is nearly impossible to determine the extent of the commercial catch that is the result of illegal fishing efforts, either in the United States or elsewhere. Literally hundreds of different regulations affect fishing enterprises, and noncompliance with any of these regulations may result in some illegal catch, much of which goes unnoticed on the high seas. It has been suggested (personal communication, S. Springer, NOAA/National Marine Fisheries Service, Office of Enforcement, 1999) that a very rough estimate of the illegal catch in U.S. waters would be on the order of several hundred thousand metric tons annually. Global figures might be 2 to 3 orders of magnitude greater.

Conventional fisheries surveillance methods in the United States and around the world are stretched beyond their capacities and are most often, despite the enormous dedication and energy of enforcement personnel, unable to cope with the scale of illegal fishing being conducted in national waters and on the high seas. Contributing to this lack of effectiveness are the lack of resources for fisheries patrols (personnel, vessels, aircraft), particularly in developing nations; the large expanses of ocean areas requiring surveillance; and the increasing size of distant water fleets.

Monitoring Exclusive Economic Zones

The ocean areas comprising the world's EEZs are often vast (see, e.g., Fig. 1). The North Pacific accounts for a surface area of 22 million km^2, while the Bering Sea covers an additional 2.3 million km^2. Constrained budgets for fisheries patrols in the Bering Sea limit the U.S. Coast Guard to only one or two high-endurance cutters and one or two C-130 aircraft to fisheries patrol duty at any given time. Contrasting with this, however, are the small island nations of the Pacific, with rich albacore tuna and swordfish stocks prevalent in their enormous EEZs. For example, Kiribati, with a land area of only 719 km^2, has an ocean EEZ of 3.5 million km^2. The Marshall Islands in the Central Pacific have a land area of 180 km^2, with an EEZ covering over 2.1 million km^2.

With little or no resources to invest in fisheries enforcement assets, these island nations by themselves

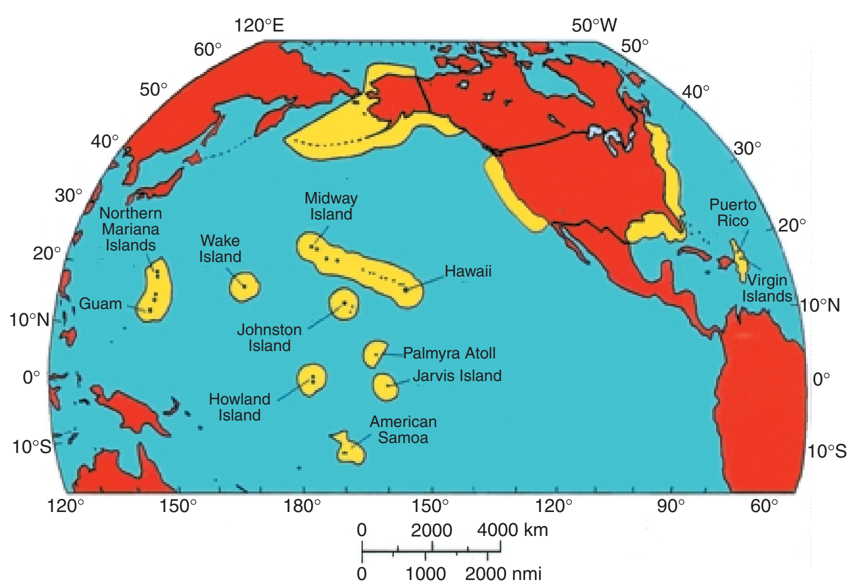

Figure 1. U.S. exclusive economic zone boundaries (yellow).

are unable to monitor their EEZs if only to restrict or reduce illegal fishing activities. A fortunate few, including the Solomon Islands and Papua New Guinea, receive international fisheries patrol assistance from countries like New Zealand and Australia. Even these patrols are limited and unable to cope with the full extent of illegal fishing in the regions.

It is clear that to effectively and efficiently monitor the ocean areas rich in commercial fish stocks, more cost-effective technologies must be made available to fisheries enforcement authorities internationally. Space-based synthetic aperture radar (SAR) sensors with wide swath capabilities, in conjunction with position-reporting beacons of vessel monitoring systems (VMS), are well suited to vastly improve the ability of seafaring nations to monitor the areas within their EEZ boundaries. Such systems cannot fully replace conventional fisheries patrol methods, but will allow large improvements in the efficiency of these conventional assets by quickly detecting suspect vessels and vectoring patrol craft to designated positions. These SAR and VMS technologies are mature and available now. Affordable systems need to be devised for all seafaring nations, especially those with very limited financial resources.

SAR DETECTION OF FISHING VESSELS

The detection of ships, including commercial fishing vessels, utilizing space-based SAR has been recognized and studied since Seasat SAR image data were initially analyzed beginning in 1982.[2,3] In-depth detection studies were conducted by Eldhuset[4] and Aksnes[5] at the Norwegian Defense Research Establishment following the launch of the European Space Agency's European Remote Sensing satellite (ERS-1) carrying a C-band, horizontally polarized SAR. Concurrent with these studies involving the hard target returns from the ships, other studies began on the detection of the surface wakes from ships—also with SAR.[6–12]

Whereas many of these studies yielded quantitative results in terms of detection thresholds as a function of such parameters as SAR incidence angle, surface wind speed, and hull lengths, only modest field campaigns validated the theoretical estimates. With the launch of Radarsat 1 in 1995, additional in-depth studies and field campaigns on ship and wake detection with SAR were carried out.[13–16] Vachon et al.[16] and Eldhuset[4] have developed radar cross sections for various fishing vessel hull lengths and, using Radarsat performance parameters, developed and validated figures of merit for ship detection as a function of incidence angle, beam modes, and wind speed. Collectively, these studies have provided the following insights into SAR-based ship detection:

- For ship detection, Radarsat standard mode (100-km swath, 25-m resolution) is better than ERS-1 SAR performance owing to the decreased clutter level for horizontal polarization.
- Ship detection performance improves with increasing incidence angle owing to the reduction in clutter level.[16]
- Ship detection performance is best with fine beam modes (45-km swath, 10-m resolution) due to their large incidence angles and high resolution.
- For ScanSAR mode (up to 500-km swath, 100-m resolution), the detection performance is best for large incidence angles, but is worse than the standard beam modes owing to the larger resolution cell size.
- The Radarsat horizontal polarization is better suited to ship detection than vertical polarization (as in ERS-1 and -2) since the clutter levels are lower for horizontal polarization at higher incidence angles.

The detection of fishing vessels with space-based SAR is now well understood. The results of studies with ERS-1 and -2 and Radarsat SAR sensors will hold true for future SAR sensors, including Radarsat 2 and Envisat. Moreover, the algorithm technology for SAR-based ship and wake detection is well advanced, and SAR workstations have been developed to support ship and wake detection applications.[4] It seems clear that the technologies exist for the application of satellite-based SAR to fisheries surveillance and enforcement on an operational basis.

Although workstation advances and algorithm refinements are needed to provide more affordable and automated ship target extraction capabilities from SAR imagery, the current state of the technology is sufficient to move forward with more advanced pilot projects and demonstration programs. These efforts will illustrate to a broad range of fisheries enforcement authorities that space-based, wide swath SAR has utility for fisheries surveillance. Complementing these ship and wake detection technologies is the fact that there are instances where significant surface slicks are evident in the SAR image (Fig. 2). These slicks are commonly associated with the discharge of fish processing waste from factory trawlers (Fig. 3) and other fishing vessels engaged in onboard fish processing. Methods for the detection of slicks associated with oil spills[17] can most likely be applied to the slicks from fish processing waste, thus adding to the collection of detectable SAR signatures associated with commercial fishing operations.

There are, however, limitations as to what aspects of commercial fishing operations space-based SAR can detect. The detection of the vessels, their wakes, and when present, surface slicks may represent the detection limits of SAR. To determine what sensors, including space-based SAR, might be capable of detecting large-scale pelagic drift nets, NOAA, in

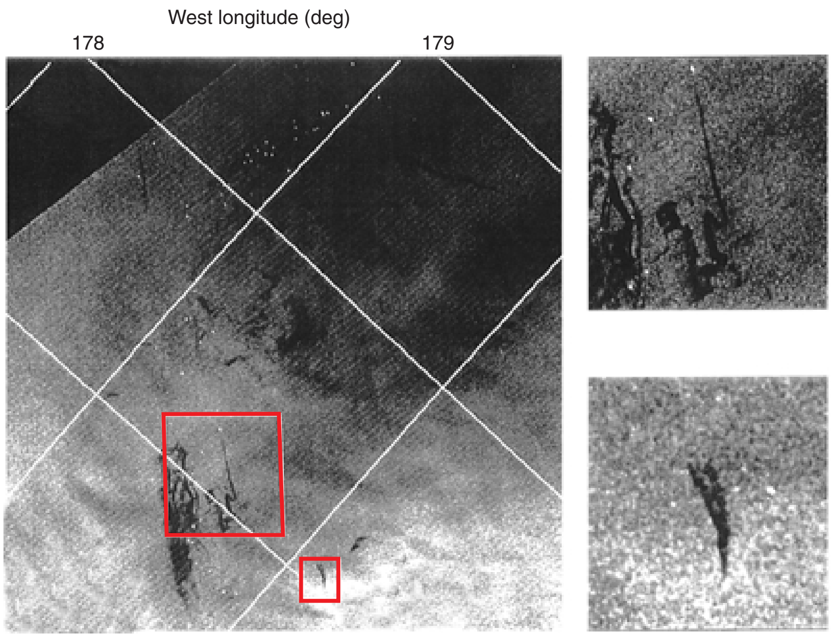

Figure 2. Radarsat SAR image showing factory trawlers and slicks produced by processing waste discharge. The two subimages on the left are enlarged to show details. (© Canadian Space Agency, 1997; provided and analyzed under the NOAA Remote Sensing Program.)

partnership with the U.S. Coast Guard and other government agencies, performed an experiment in October 1998 using fishing gear simulating a drift net[18] (Fig. 4). Data from four Radarsat passes over the simulated drift nets, using the wide, standard, and fine beam modes under various surface wind conditions, failed to show any signatures that might be associated with them. The vessels that set the simulated drift nets were, however, detected in the standard and fine mode images.

Fisheries Demonstration Projects

The Norwegian Defense Research Establishment has initiated pilot projects using ERS-1 SAR to monitor fishing vessel activities in the Barents Sea.[19,20] A number of papers describe other demonstrations, both proposed and actual, aimed at the use of space-based SAR to aid the fisheries surveillance problem.[21–24] In nearly all cases, the authors illustrated that the SAR technology was both capable and ready to support fisheries enforcement applications, and that sufficient sensors would be available in early 2000 to provide the coverage and revisit capabilities needed for effective ocean monitoring.

Vessel Monitoring Systems

Conventional VMS consist of a beacon (transponder) located onboard a vessel capable of automatically reporting the vessel's position through a satellite communications link (usually Inmarsat-C) to a shore-based terminal (Fig. 5). Several U.S. and foreign fisheries require fishing vessels to carry VMS units as a condition of licensing and operating within the fishery. The United States has such a fishery in Hawaiian waters and will soon require VMS utilization in the Atka mackerel fishery in Alaska. The Australian Defense Force has recently funded a VMS involving some 1500 vessels operating in the South Pacific within the jurisdiction of the Fisheries Forum Agency representing 16 member countries of the Central and South Pacific. This system includes a fully integrated geographic information system and is the world's largest system using Inmarsat-C.

The Fisheries Forum Agency VMS is indicative of the trend in international fisheries enforcement to monitor and control commercial fishing operations within national waters. Unfortunately, the effective use

Figure 3. Fish processing waste discharge (reproduced by permission of Greenpeace, U.S.A.).

Figure 4. Floats used on simulated large-scale pelagic drift net.

Figure 5. A conventional vessel monitoring system.

of VMS requires vessel operators to cooperate and adhere to the regulations. Vessels wishing to fish illegally are still able to do so, although at higher risk than in areas without VMS utilization. VMS are affordable ($1K–$2K U.S.) and commercially available, and operate under all weather conditions. However, they are not sufficient in themselves to provide full monitoring capabilities of fishing vessel operations.

An Integrated SAR and VMS

Several researchers have studied integrated systems involving space-based SAR augmented with other space-based sensors. These systems have included the Advanced Very High Resolution Radiometers (AVHRRs) and high-resolution optical sensors.[14,15]

Each of these augmenting sensors has limitations. For example, the AVHRR (for the detection of vessel-generated cloud scars) is limited by atmospheric conditions conducive to stack gas scar formation. Optical systems are limited by cloud cover and lack of daylight. A system integrating VMS with space-based SAR can provide global, all-weather, day–night capability. Such a system is simple and straightforward in that it does not require sophisticated spectral analysis or subpixel processing to be effective. Whereas such a system may be limited to the detection of vessels 20 m or greater in length, it will still be useful. Moreover, public awareness that space-based SAR has been used to find even a few vessels illegally fishing will serve as an effective deterrent to at least some additional illegal catches.

The blended SAR and VMS position information will quickly show vessels that are not reporting by VMS (Fig. 6). With such information, patrol craft can be vectored to the suspect vessel for identification and for determining its legal status. In contrast to wide-area reconnaissance missions, patrol craft can be utilized more efficiently using the cuing provided by the combined SAR and VMS information.

Requirements for System Implementation

It is evident from the preceding discussion that the requirements for the implementation of an operational, integrated SAR and VMS for fisheries enforcement are not technological. The barriers to implementation are more logistical and involve affordability and resource availability issues. With the launch in the early 2000 time frame of Radarsat 2, Envisat, and commercial SAR satellites with multimode performance providing high-resolution modes and wide swath (100-km or greater) capabilities, sufficient SAR satellites will be available to provide the needed coverage and continuity of SAR data sufficient to warrant investments in SAR/VMS integration. The requirements for making SAR/VMS available for fisheries enforcement are as follows:

- *Affordable SAR data.* All indications are that space-based SAR data, like Radarsat 1 data, will continue to be sold to users. Unfortunately, the pricing policy established for Radarsat 1 has placed the cost of SAR

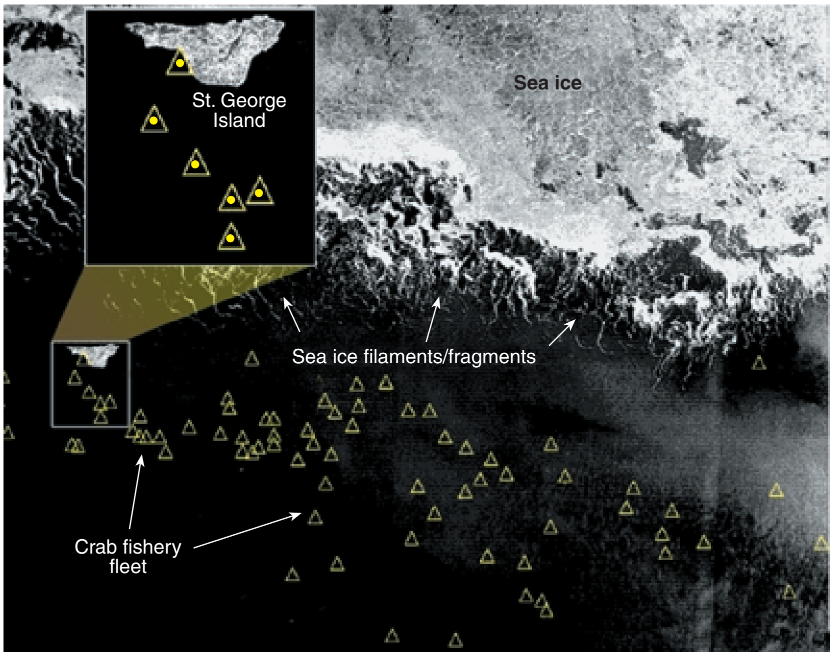

Figure 6. SAR image with simulated blending of SAR and VMS data. Triangles depict VMS reporting vessels. (© Canadian Space Agency, 1998; SAR image provided under the NOAA Ocean Remote Sensing Program.)

data too high for many users ($1.5K–$4K per image). This is especially true for users of ocean data, where the data are highly perishable owing to the transient nature of ocean surface conditions, and for users with monitoring applications. SAR pricing policies must be tailored to a user's application, with lower prices available for ocean monitoring applications such as in a fisheries enforcement system. For this application, SAR data must be available for hundreds of dollars per image, not thousands.

- *Near–real-time SAR collection and processing.* SAR data for fisheries enforcement applications must be available to the user within 3–6 h of the observations. Near–real-time processing will be required using predicted orbit parameters to produce Earth location accuracies in the 0.5–1.0-km range. With dedicated direct downlink capabilities of future SAR satellites, coupled with an increasing number of SAR-capable ground stations, transportable stations, and affordable SAR processors, it will be possible to achieve this capability in early 2000.
- *Affordable workstations.* Although adequate SAR workstations with functional detection algorithms are now available, their costs are still prohibitive to many users—especially new users (as are most fisheries enforcement authorities) and those with limited resources. The need is for PC-based workstations with detection algorithms capable of running on high-end, Windows-based computers like those used by fisheries enforcement and management personnel.
- *Detection algorithms.* Algorithms for the detection of ships, wakes, and slicks exist now. While mostly automated, most algorithms require some operator supervision. They need additional refinement to be more automated, to be PC-compatible, and to be usable by operators with little familiarity with SAR. Algorithms meeting these requirements are being developed, and will be available commercially in 2001.
- *VMS licensing requirements.* For an integrated SAR/VMS to be effective for any given fishery, licensing regulations must mandate that all vessels in the fishery have a VMS installed and operational. Because costs are involved, and because most fishing vessel operators are highly reluctant to be "monitored" by fisheries authorities, there will be resistance by commercial fishermen to accept a VMS. Considerable political maneuvering will be required to establish VMS-based licensing requirements, and a mechanism must be established to ensure the security of all position information provided by these systems.
- *Funding and resource needs.* The costs associated with establishing and operating an integrated SAR/VMS may be significant for many users, especially in developing countries. For some users, acquiring the monitoring data from value-added providers may be the most cost-effective means of operating. Satellite communications and the Internet make this possible. For other enforcement users, an in-country capability is desirable and/or required. Investments for capitol equipment can be in the $300K–$1M range, with operating costs being a function of affordable SAR data pricing policies. These operating costs should not exceed $1M per year, and SAR data would find broader acceptance in fisheries enforcement with costs in the $300–$500K range per year. One strategy to obtain funds necessary to finance an integrated SAR/VMS is illustrated in Fig. 7. Revenue could be provided by fines and forfeitures obtained from illegal fishing activities. Portions of the licensing fees could be allocated to system implementation and operation. In some instances, governments may provide funds for initial implementation, possibly by drawing from savings realized from more efficient use of conventional patrol assets.

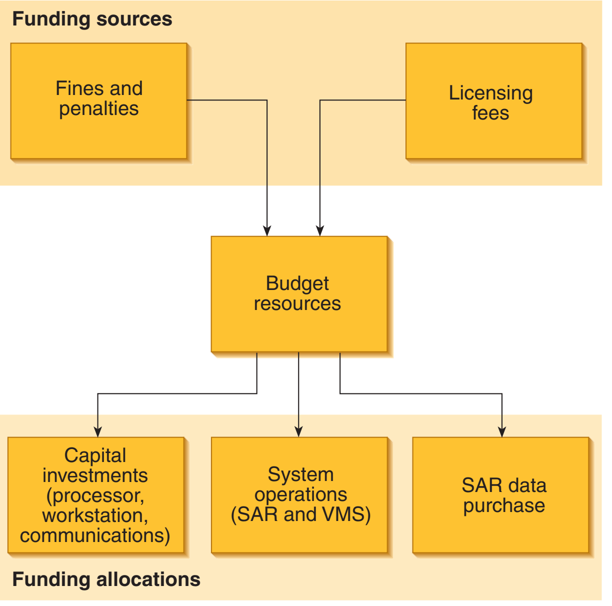

Figure 7. A funding strategy for an operational integrated SAR/VMS for fisheries enforcement applications.

CONCLUSION

The need for improved surveillance and control of commercial fishing activities on a global scale is urgent. Without this improvement, fish stocks will continue to decline and collapse. The technologies exist now and refinements are under way to provide these improvements using space-based, wide swath SAR and VMS. The key challenges remaining are to produce SAR data affordably and to garner the political will to establish VMS requirements for the world's fisheries.

REFERENCES

[1]Alverson, D. L., and Larkin, P., "Fisheries: Fisheries Science and Management, Century 21," in *Proc. World Fisheries Congress*, Athens, Greece (May 1992).

[2]Fu, L.-L., and Holt, B., *SEASAT Views Oceans and Sea Ice with Synthetic Aperture Radar*, Publication 81–20, JPL, Pasadena, CA (1982).

[3]Vesecky, J. F., and Stewart, R. H., "The Observation of Ocean Surface Phenomena Using Imagery from the Seasat Synthetic Aperture Radar: An Assessment," *J. Geophys. Res.* **87**(C5), 3397–3430 (1982).

[4]Eldhuset, K., *Automatic Ship and Ship Wake Detection in Spaceborne SAR Images from Coastal Regions*, FFI/Report—87/9001, Norwegian Defense Research Establishment, Kjeller, Norway (1987).

[5]Aksnes, K., *SAR Detection of Ships and Ship Wakes*, ESA Contract Study Report, Vol. 2: Main Volume, Norwegian Defense Research Establishment, Kjeller, Norway (1988).

[6]Eldhuset, K., *Digital Image Processing for Maritime Surveillance with Spaceborne Synthetic Aperture Radar*, FFI/Report—87/9001, Norwegian Defense Research Establishment, Kjeller, Norway (1987).

[7]Lyden, J. D., Aammond, R. R., Lyzenga, D. R., Shuchman, R. A., and Kasischke, E. S., "Synthetic Aperture Radar Imaging of Surface Ship Wakes," *J. Geophys. Res.* **93**(C10), 12,293–12,303 (1988).

[8]Milgram, J. H., "Theory of Radar Backscatter from Short Waves Generated by Ships, with Application to Radar (SAR) Imagery," *J. Ship Res.* **32**(1), 54–59 (1998).

[9]Griffen, O. M., Peltzer, R. D., Reed, A. M., and Beck, R. F., "Remote Sensing of Surface Wakes," *Nav. Eng. J.*, 245–258 (1992).

[10]Shurmann, S. R., "Radar Characterization of Ship Wake Signatures and Ambient Ocean Clutter Features," in *Proc. 1989 National Radar Conf.*, pp. 182–187 (1989).

[11]Wahl, T., Eldhuset, K., and Skoelv, A., "Ship Traffic Monitoring Using ERS-1 SAR," in *Proc. First ERS-1 Symp.—Space at the Service of Our Environment*, **ESA SP-359**, pp. 151–154 (Mar 1993).

[12]Gower, J. F. R., Vachon, P. W., and Edel, H., "Ocean Applications of Radarsat," *Can. J. Remote Sens.* **19**(4), 372–383 (1993).

[13]Skoelv, A., Anderson, T., Eldhuset, K., and Wahl, T., "Ship Traffic Monitoring and Oil Spill Detection Using ERS-1 SAR," in *Remote Sensing—From Research to Operational Applications in the New Europe, Proc. 13th EARSel Symp.*, pp. 19–26 (1994).

[14]Freeberg, M., Wrigley, R., Dunlop, D., Sullivan, D., and Staples, G., "Application of Space-Based Radar Systems to Fisheries Monitoring, Control, and Surveillance," in *Proc. Third Thematic Conf. on Remote Sensing for Marine and Coastal Environments*, Seattle, WA (18–20 Sep 1995).

[15]Freeberg, M., and Amjoun, B., "Vessel Monitoring, Control and Surveillance (MCS) from Space: Promise Approaching Practicality," in *Proc. 4th North Pacific Rim Fisheries Conf.*, Tokyo, Japan (22–24 Apr 1997).

[16]Vachon, P. W., Campbell, J. W. M., Bjerkelund, C. A., Dobson, F. W., and Rey, M. T., "SAR Detection by the Radarsat SAR: Validation of Detection Model Predictions," *Can. J. Remote Sens.* **23**(1), 48–59 (1997).

[17]Lindberg, D., and Wahl, T., *Automatic Screening of SAR Images for Slick Detection*, NDRE/FFI Final Report, Norwegian ERS-1 Oil Spill Detection Project, Kjeller, Norway (1995).

[18]Montgomery, D. R., *Final Report—Radarsat Measurements of Simulated Large-Scale Pelagic Drift Nets*, JPL, Pasadena, CA (Feb 1999).

[19]Wahl, T., *Are Radar Satellites Cost-Effective for Maritime Surveillance?* Paper No. IAA-95-IAA.1.3.04, 46th IAF Conf., Oslo, Norway (1995).

[20]Wahl, T., "Integrated Use of Radar Satellites for Fisheries Enforcement Operations," in *Proc. 27th Int. Symp. on Remote Sensing Env.*, pp. 123–125 (8–12 Jun 1998).

[21]Freeberg, M. H., "Application of Space-Based Radar Systems to Fisheries Monitoring, Control and Surveillance," in *Proc. Third Thematic Conf. on Remote Sensing for Marine and Coastal Environments*, Seattle, WA (18–20 Sep 1995).

[22]Montgomery, D. R., Pichel, W., and Clemente-Colón, P., "The Use of Satellite-Based SAR in Support of Fisheries Enforcement Applications," in *Proc. 27th Int. Symp. Remote Sens. Env.*, pp. 131–134 (8–12 Jun 1998).

[23]Clemente-Colón, P., Montgomery, D., Pichel, W. G., and Friedman, K., "The Use of Synthetic Aperture Radar as a Potential Indicator of Fishing Activity in the Bering Sea," in *Proc. Pacific Ocean Remote Sensing Conf. (Porsec '98)*.

[24]Montgomery, D., Pichel, W., and Clemente-Colón, P., "SAR Experiments in Support of Fisheries Enforcement Applications," in *Proc. Int. Geoscience and Remote Sens. Symp. (IGARSS '98)*, Seattle, WA, on CD-ROM (6–10 Jul 1998).

THE AUTHOR

DONALD R. MONTGOMERY is affiliated with NASA/Jet Propulsion Laboratory, California Institute of Technology, in Pasadena. His e-mail address is donm1@cdsnet.net.