

SAR Needs and Requirements for Operational Ocean Management Applications

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ABSTRACT

Government agencies involved in operational ocean management activities such as fisheries enforcement, marine sanctuary management, and hazard response are beginning to use synthetic aperture radar (SAR) data and derived products in carrying out their operational mission. SAR-derived environmental measurements of interest include: coastal winds, wave parameters, ice parameters, oil spill location, vessel positions, and near-shore bathymetry. These measurements are useful for (1) weather and ocean forecasting, (2) marine ecosystems management, (3) cryospheric monitoring, (4) hazard response, and (5) climate research. In the last few years, requirements for satellite SAR data have been well documented in the U.S., Canada, and Europe, and operational marine agencies have become more assertive in requesting and learning to use SAR-derived products in support of their mission. This paper focuses on the SAR-related marine measurement and SAR-system requirements of agencies with an operational ocean management mission. Illustrations are given of some of the SAR-derived products useful for ocean management applications.

Keywords: Ocean Management, Synthetic Aperture Radar, Winds, Waves, Ice, Vessels

1 INTRODUCTION

A number of environmental parameters and products derived from synthetic aperture radar (SAR) are now mature enough to be useful in operational ocean management. In some cases, they already are being used in an operational or quasi-operational fashion. Here we define “operational ocean management” as activities related to the ocean environment which are underway on a routine ongoing basis in agencies to fulfill their missions, activities such as fisheries enforcement, marine sanctuary management, and hazard response. This paper is focused on the SAR-related needs and requirements of these agencies. Requirements are broken down into measurement requirements and application requirements. Some of these ocean management applications are illustrated.

2 MEASUREMENT REQUIREMENTS

Increasingly, remote sensing research and development has become a requirements-driven process. New satellite systems are being designed and built only after an extensive user requirement definition process; and operational product processing software is developed only after gathering user requirements, and after user evaluation of prototype products provided in applications demonstrations.

In the U.S., formal requirements gathering exercises have been completed for the next generation of both polar and geostationary operational satellite systems. Requirements for the National Polar Orbiting Operational Satellite System (NPOESS), the next generation of NOAA and Department of Defense polar meteorological satellites, are consolidated in the Integrated Operational Requirements Document (IORD) [1]. The GOES-R Requirements Document [2] contains the observation requirements for the next generation of geostationary satellites, the Geostationary Operational Environmental Satellite (GOES) –R series. The NPOESS Integrated Program Office also sponsored the development of a requirements document for a study of an Ocean Observer Satellite which has not been funded. This document, the Ocean Observer User Requirements Document (OOURD) [3], contains the most extensive compilation of SAR-related requirements of any of the existing requirements documents. In addition, the Navy/NOAA/Coast Guard tri-agency National Ice Center has documented its requirements in the National Ice Center Requirements List for Environmental Satellites [4]. The most recent satellite requirements gathering efforts are summarized in the Consolidated Observation Requirements List (CORL) [5] which is still under development.

The design of the next generational of radar satellites in Europe and Canada will also be driven largely by requirements which are documented in the Mission Requirements Document for the European Radar Observatory Sentinel-1 [6], and the RADARSAT Constellation User Requirements Document [7]. These documents include ocean, land, atmosphere, and even space environmental measurement requirements, but they differ in which parameters are included, and in the details of how the parameters are described. The following marine-related SAR-derived parameters can be found in some, but not all of these documents:

- Coastal sea surface winds and wind stress
- Wave characteristics – significant wave height, wave direction, wavelength
- All weather day/night imagery
- Oil spill location
- Vessel positions
- Bathymetry (near shore)
- Littoral currents
- Surf conditions
- Ocean mesoscale features – fronts, eddies, current boundaries, river plumes, upwelling
- Internal waves and mixed layer depth estimates
- Sea and lake ice – concentration, age, motion, edge location, thickness
- Ice of land origin (*i.e.* icebergs)
- River ice location/condition
- Mesoscale and microscale atmospheric features – barrier jets, gap winds, storms, fronts, etc.

Table 1 illustrates a representative requirements definition. There are actually two sets of requirements given: (1) the threshold – a minimally acceptable set of requirements, and (2) the objective – what is really desired if technically and economically feasible. Note that coastal coverage refers to the areal extent consistent with the U.S. Exclusive Economic Zones (EEZ), which extend 370 km from shore. Coastal coverage shall entail roughly 300 km swath coverage, but pertains to all coasts worldwide to support civil and military. This EDR also pertains to selected open ocean areas. The parameter is a measure of atmospheric wind speed/direction at the sea/atmosphere interface (10 meter height neutral stability winds) in clear sky and cloudy conditions, for integrated rainfall rates less than $2 \text{ mm hr}^{-1} \text{ km}^{-2}$. Wind stress measurements observe the frictional stress of the wind acting on the sea surface, causing it to move as a wind-drift current, and causing the formation of waves.

3 OCEAN MANAGEMENT APPLICATIONS

The above SAR-derived measurements are used individually and collectively to aid a growing number of marine management applications, and there are many ways to group these applications. Here we organize them into the following major categories: (1) Weather and Ocean Forecasting, (2) Marine Ecosystems Management, (3) Cryospheric Monitoring, (4) Hazard Response, and (5) Climate Change.

Table 1. Coastal Sea Surface Wind Requirements from the NPOESS IORD-II [1]

Systems Capabilities	Thresholds	Objectives
a. Horizontal Cell Size	1 km	300m
b. Minimum distance to shore	1 km	300 m
c. Mapping Uncertainty	1 km	300 m
d. Measurement Range		
1. Wind Speed / Direction	3 to 35 m s ⁻¹ , 0 to 360°	2 to 50 m s ⁻¹ , 0 to 360°
2. Wind Stress / Direction	0 to 3 N m ⁻² , 0-360°	0 to 10 N/m ² , 0-360°
e. Measurement Uncertainty (Wind Speed and Direction)		
1. Speed**	greater of 2 m s ⁻¹ or 10 %	greater of 1 m s ⁻¹ or 10 %
2. Direction ***	TBD	10°
f. Measurement Precision (Wind Stress)		
1. Speed	0.02 N m ⁻²	0.01 N m ⁻²
2. Stress Direction	TBD	TBD
g. Measurement Accuracy (Wind Stress)		
1. Stress	0.02 N m ⁻²	0.01N m ⁻²
2. Stress Direction	TBD	TBD
h. Refresh	6 hours	2 hours
i. Latency	2 hours	1 hour
j. Geographic Coverage	U.S. EEZ up to coast and in lakes, bays and estuaries; selected open ocean regions worldwide not to exceed 30 minutes each orbit	U.S. EEZ up to coast and in lakes, bays and estuaries; selected open ocean regions worldwide not to exceed 30 minutes each orbit

** Not more than 25% of the wind speed uncertainty should be attributed to a wind speed bias (*i.e.*, no more than 6.25% of the square of the RMS error should be due to the bias).

*** Direction uncertainty is to be applied to the unique chosen ambiguity.

3.1 Weather and Ocean Forecasting

Table 2 contains some of the weather and ocean forecasting marine applications which can utilize SAR-derived measurements. Figure 1 is an example of a SAR wind image currently being used experimentally by meteorologist in Alaska for coastal wind analysis and prediction.

Table 2. Weather and Ocean Forecasting Applications Aided by SAR-derived Measurements

#	Application	Useful SAR-derived Measurements
1	Safety of Marine Transport	Winds, waves, vessels, currents, atmospheric features
2	Safety of Low-flying aircraft	Winds, atmospheric features
3	Safety of Fishing Activities	Same as #1 above
4	Search and Rescue	Winds, waves, vessels, currents, surf, atmospheric features

3.2 Marine Ecosystems Management

Table 3 lists some of the SAR applications and measurements applicable to Marine Ecosystems Management, and Figure 2 is an example of a ship detection product currently employed in fisheries enforcement.

Table 3. Marine Ecosystems Management Applications Aided by SAR-derived Measurements

#	Application	Useful SAR-derived Measurements
1	Marine Sanctuary Management	Vessel positions, ocean mesoscale features, estimates of mixed layer depth, internal wave location
2	Fisheries Enforcement	Vessel positions
3	Fisheries Management and Research	Vessel positions, ocean mesoscale features, estimate of mixed layer depth

3.3 Cryospheric Monitoring

Table 4 contains a list of cryospheric applications and the corresponding measurements needed to support these applications. Figure 3 is an example of a SAR ice image used for ship routing in support of McMurdo Antarctic resupply.

Table 4. Cryospheric Monitoring Applications Aided by SAR-derived Measurements

#	Application	Useful SAR-derived Measurements
1	Marine and Northern Lake Transportation Safety	Sea and Lake Ice: concentration, age, motion, edge location, floe size, iceberg location
2	Safety of Oil Industry Operations	Sea ice: concentration, age, motion, edge location, floe size, iceberg location
3	Safety of Fisheries and on-ice Activities	Same as #1 above
4	River Transportation Safety	River Ice Conditions

3.4 Hazard Response

Table 5 lists hazard response applications and the SAR-derived measurements which aid in these applications. Figure 4 is an example of SAR imagery used in location of oil spills after hurricane landfall.

Table 5. Hazard Response Applications Aided by SAR-derived Measurements

#	Application	Useful SAR-derived Measurements
1	Safety of Life and Property	Oil spill location, oil platform change, coastal bathymetry, flood mapping, high-resolution winds
2	Ecosystem Protection	Oil Spill Location, coastal change detection, coastal wetland mapping, flood mapping, high-resolution winds, runoff plumes/sewage spills
3	Endangered Species Protection	Oil spill location
4.	Marine Debris Location	Ocean mesoscale features – fronts and eddies

3.5 Climate Research

Table 6 lists some of the climate applications for which SAR-derived measurements can make a contribution. Figure 5 is a sample SAR product being used for climate studies. Information on coastal wind climatology is proving useful in deciding where to locate offshore wind farms [9] and for studies of locations and frequency of dangerous coastal wind conditions, information that can provide valuable guidelines for meteorological forecasting [10].

Table 6. Climate Applications Aided by SAR-derived Measurements

#	Application	Useful SAR-derived Measurements
1	Guidelines for Meteorological Forecasting	Coastal winds
2	Wind Farm Location	Coastal winds
3	Marine Engineering	Coastal winds, waves, all ice measurements
4	Global Climate Change Studies	All ice measurements

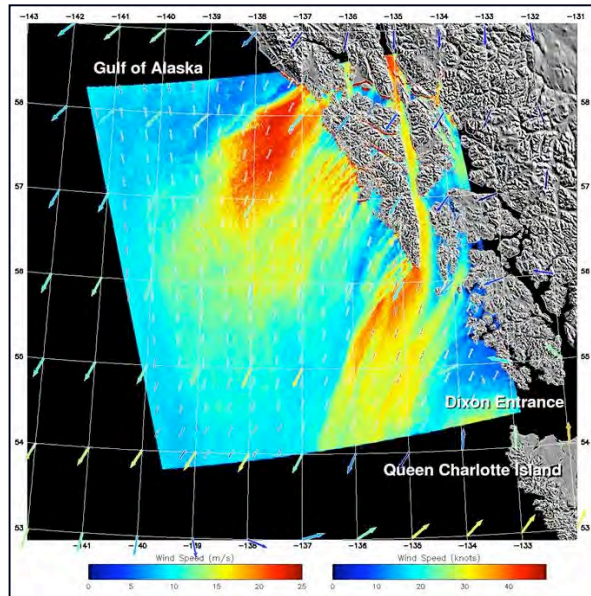


Figure 1. SAR wind image for Southeast Alaska coast. Color indicates SAR wind speed. Directional arrows are from the Navy Operational Global Analysis and Prediction System (NOGAPS). SAR winds have sub-kilometer resolution allowing wind calculations in straits, fjords, and lakes as well as right up to the coast.

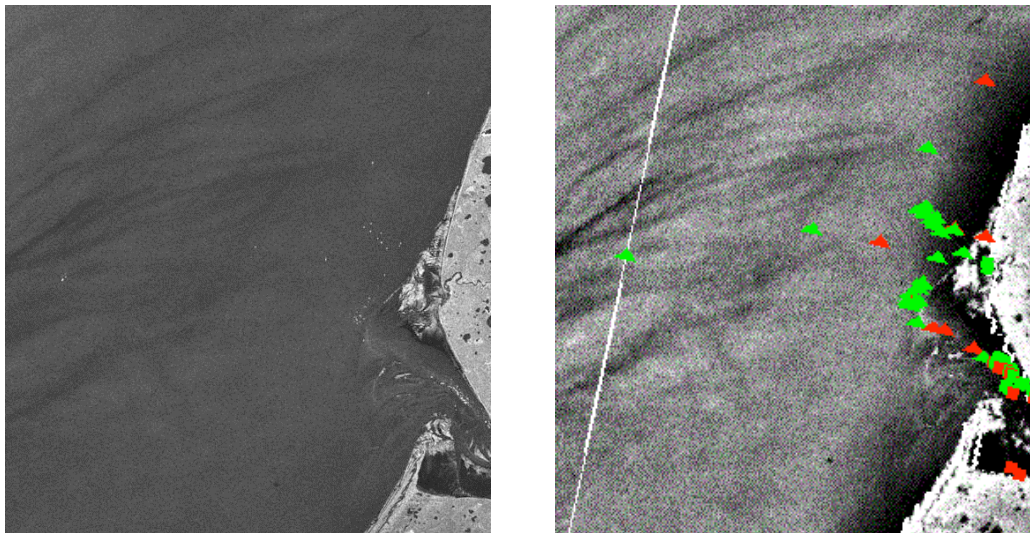


Figure 2. Left: Radarsat-2 SAR image for July 5, 2004 04:11 UT of the Bristol Bay, Alaska coast. The Bay at the right bottom of the image is Egegik Bay, Alaska. Right: Ship detection image where triangles are ship detections in the open ocean, squares are ship detections within 5 km of a coastline, green indicates strong targets, red indicates weak targets. The white line is a nadir ambiguity. SAR Imagery © Canadian Space Agency, 2004.

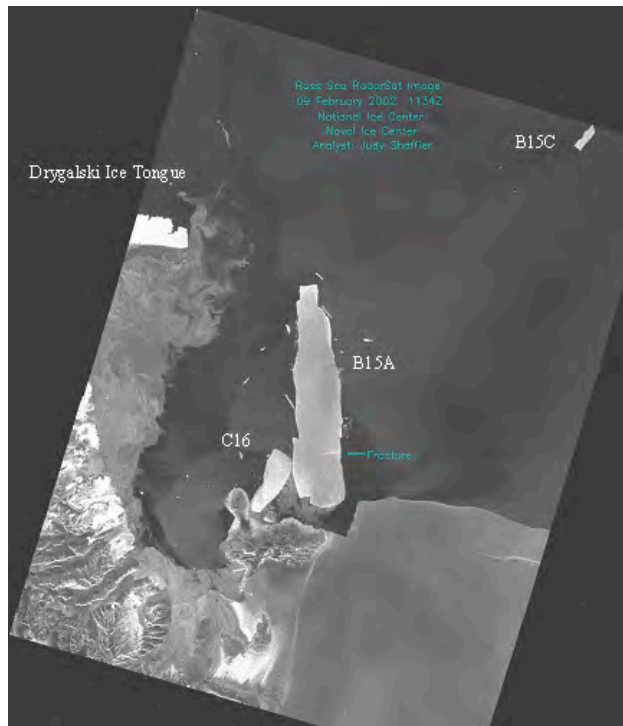


Figure 3. Radarsat-1 image of large tabular Antarctic icebergs in the Ross Sea. Image is from February 9, 2002 at 11:34 UT. Image © Canadian Space Agency, 2002.

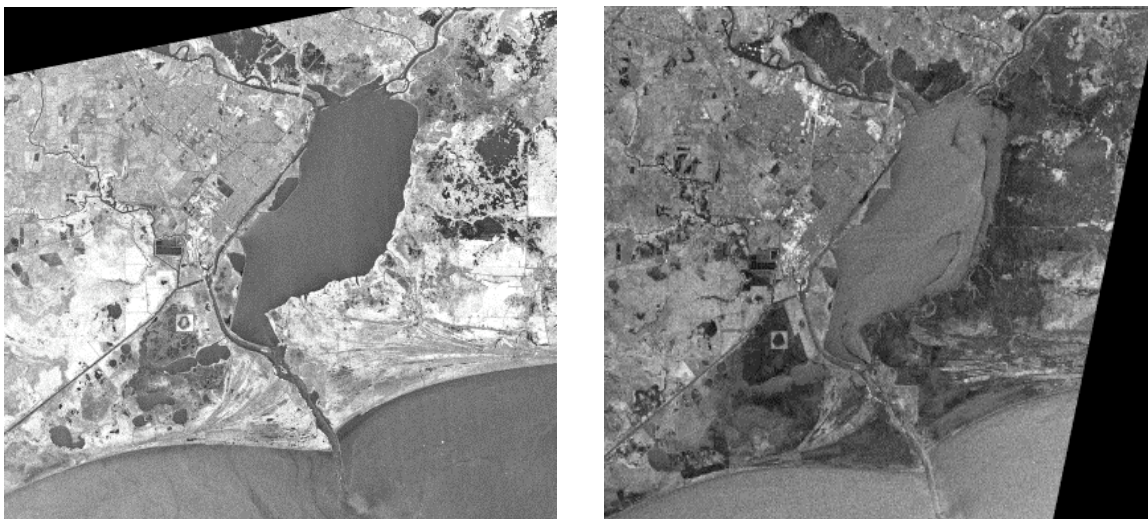


Figure 4. Radarsat-1 imagery of Sabine Lake on the Louisiana/Texas border (north at the top, the Gulf of Mexico at the bottom). The left image was taken May 26, 2004, more than a year before the passage of Hurricane Rita. The right image was taken September 25, 2005, shortly after the passage of Hurricane Rita. The oil slicks which can be seen near the eastern shore of the lake were confirmed by NOAA aircraft flights [8]. Radarsat-1 imagery © CSA, 2004

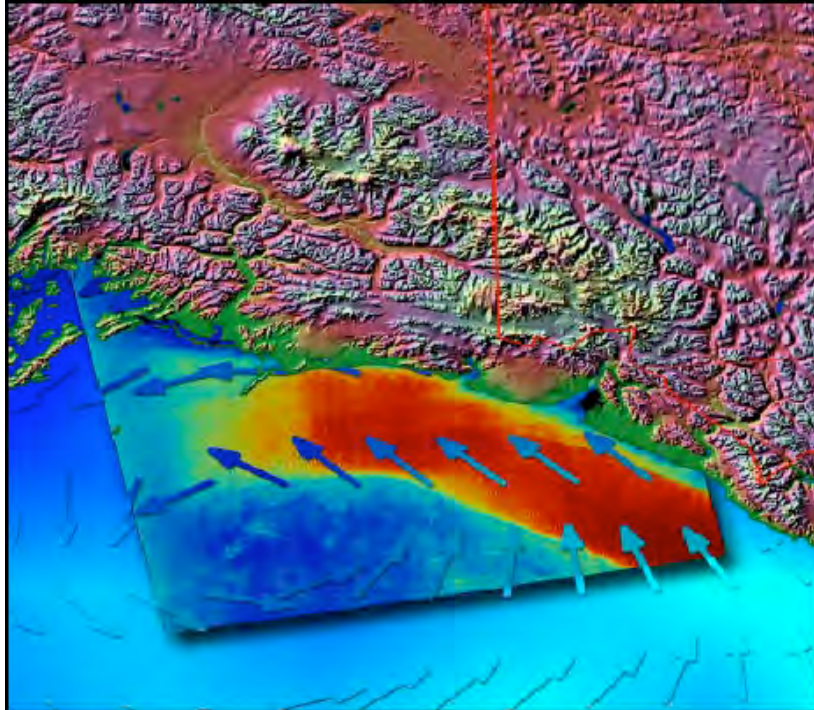


Figure 5. SAR wind image of coastal barrier jet along the northern coast of the Gulf of Alaska (Prince William Sound is in the middle-left edge of the image). Image is from RADARSAT-1 data taken September 4, 2000 at 03:06 UT [11]. Arrows show wind direction from the Navy Operational Global Analysis and Prediction System (NOGAPS) meteorological model (red is high winds, blue is low).

4 USER NEEDS

The Alaska SAR Demonstration (AKDEMO) is a near-real-time demonstration of SAR-derived products with the goal of evaluating product usefulness to operational agencies [12]. This demonstration has operated continuously since October 1999, providing products from the Canadian Space Agency's RADARSAT-1 satellite with occasional products derived from the European Space Agency's ENVISAT satellite. These products have proven to be of use to the following marine operations personnel:

- Weather Service meteorologists, hydrologists, and ice forecasters
- Coast Guard fishing enforcement officers
- Search and rescue personnel
- Hazardous materials spill responders
- Ferry boat and shipping vessel captains
- Coastal survey vessel captains
- Marine sanctuary managers
- Fisheries researchers and managers

From feedback obtained in three training courses taught in Alaska and ongoing contact with users in Alaska, we find that operational users are transitioning from curiosity and occasional use to the routine application of SAR products in their day-to-day activities. Users are now asking to work collaboratively with SAR product producers to learn how best to incorporate SAR imagery and products in their ocean management activities. New applications have emerged, such as marine sanctuary monitoring, hurricane hazard response, marine debris location, and climatologic coastal wind studies. But that is not to say that experienced and new users are satisfied with the SAR-derived products they are currently obtaining. U.S. users would like the following (which they are currently not receiving):

- Operational availability of imagery and products rather than research case studies and applications demonstrations
- More widespread coverage to include all the U.S. coastlines (particularly the conterminous 48 states)
- More frequent repeat coverage
- Data and products delivered within one hour
- All products and data available in formats already familiar to operational users (e.g., file formats compatible with geographic information systems)
- Wave products
- Ice thickness products

In addition to the above shortcomings, there are other barriers to the complete adoption of the results of SAR research into the user domain. One-on-one collaboration and extensive tailoring is often required for complete acceptance, a service which is often limited by lack of personnel and resources. The results of scientific research must often be translated into the user's language and operational culture to be most effective. In addition, there is the perennial problem that SAR imagery is unlike visible and IR imagery, and thus is often hard to interpret without extensive experience and training. Unless the imaging mechanism and how the radar signal interacts with the ocean environment are well understood, SAR imagery interpretation is sometimes counterintuitive. These problems are, however, slowly being overcome. Two new SAR interpretation manuals, a SAR Marine User's Manual [13] and a SAR Wind User's Guide [11] are now available, and provide substantial guidance and sample imagery to aid inexperienced users.

5 OPERATIONAL SAR SYSTEM REQUIREMENTS

In addition to the SAR-derived measurement requirements summarized above, the five operational ocean management applications discussed earlier require certain characteristics of the SAR satellite and data system. The following summaries these characteristics, distilled from requirements documents [1,2,3,4,5,6,7] and experience with users.

Table 7. Geographic Coverage Requirements for Ocean Management Applications

Ocean Management Application	Geographic Coverage Requirements
Weather and Ocean Forecasting	Exclusive Economic Zone (EEZ) and adjacent ocean regions
Marine Ecosystem Management	Marine sanctuaries, maritime borders, fishing areas and boundaries, EEZ, port approaches, and adjacent ocean regions (out to 1000 nm)
Cryospheric Monitoring	All ice-covered ocean regions globally, tidewater glaciers, ice-covered rivers and lakes
Hazard Response	Regions with or susceptible to oil spills; regions impacted by hurricanes; flooded coastal regions and river basins
Climate	EEZ and adjacent ocean regions, Arctic, Antarctic

Table 8. Resolution and Swath Width Requirements for Ocean Management Applications

Ocean Management Application	Resolution and Swath Width Requirements
Weather and Ocean Forecasting	Low res* /wide swath** for winds and large vessels, and high res* / standard swath** for waves, ocean features, and small vessels
Marine Ecosystem Management	Low res / wide swath and high res / standard swath.
Cryospheric Monitoring	Low res / wide swath for polar, open ocean, and coastal monitoring, and some high res / standard swath for estuaries, channels, and inlets
Hazard Response	Very high res (3-5 m) / narrow swath (25-50 km) for small oil spills and marine debris; high res /standard swath for moderate oils spills and flooding; occasional low res /moderate swath (250-350 km) for large oil spills.
Climate	Same as Weather and Ocean Forecasting

* Low resolution defined as 50-100 m, High resolution defined as 10-25 m

** Wide swath defined as 300-600 km, Standard swath defined as 50-150 km

Table 9. Timeliness Requirements for Ocean Management Applications

Ocean Management Application	Timeliness Requirements
Weather and Ocean Forecasting	1/2 to 2 hours
Marine Ecosystem Management	15 min to 1 day
Cryospheric Monitoring	1 hour (navigation) to 6 hours (daily and weekly charts)
Hazard Response	15 min to 2 hours
Climate	Months to years

Other satellite and data system requirements common to many or all of the illustrated ocean management applications include revisit frequency, acquisition characteristics, scheduling, and continuity.

- Revisit Frequency – Revisit requirements vary with individual measurements and applications ranging between hours and days. To achieve revisit frequencies more than once every 2-4 days in general requires access to multiple satellite systems.
- Acquisition Characteristics – Ability to obtain data over regions not served by direct reception (*i.e.*, with an on-board recorder or satellite relay system); ability to acquire, process, and distribute data from desired geographic areas within timeliness constraints; and ability to provide Level 1 imagery (*i.e.*, a normal amplitude image) with some Level 0 and complex data (*i.e.*, data containing both amplitude and phase information).
- Acquisition Scheduling –
 - Routine coverage: Scheduling 1-2 months in advance, with occasional schedule modification up until a few days before acquisition
 - Hazard coverage or ship operations support: Scheduling 1-4 days in advance, with occasional modification up until 12 hours before acquisition
- Schedule Visibility – The schedule should be visible to all user organizations (unless acquisition is for national security) to maximize scheduling efficiency and usefulness.
- Continuity - SAR satellite systems should be designed for at least 15 years. Many operational agencies will not make the necessary investments in training, infrastructure, and development of data assimilation techniques to adopt a new technology without assurances that the data will be available continuously on an operational basis.

6 SUMMARY

SAR instruments can provide many measurements and derived products of use to operational ocean management - measurements such as winds, waves, ice concentration/age/motion/edge location, oil spill location, and ocean/atmospheric features. Requirements for these measurements are now well documented in the U.S., Canada, and Europe. Increasingly, SAR-derived products are being used routinely in operational marine agencies for (1) weather and ocean forecasting, (2) marine ecosystems management, (3) cryospheric monitoring, (4) hazard response, and (5) climate change research. However, to be fully utilized operationally, SAR systems must provide timely data covering marine areas of operational interest with sufficient resolution and revisit frequency to support the missions of these operational agencies. And there must be a reasonable chance that these data and products will be available for a period of at least 15 years before agencies are willing to make the needed investments in training, infrastructure, and data assimilation techniques.

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