ABSTRACT

The 2nd workshop on Coastal and Marine Applications of Synthetic Aperture Radar was held in Svalbard Norway on 8-12 September 2003. This conference was focused on providing an overview of the tools now available within the international community for utilizing synthetic aperture radar (SAR) systems to characterize the marine environment. Applications were specifically focused on wind, waves, sea ice, and currents. This paper provides an overview of the discussions from that workshop and proposes the next steps along the road of achieving true operational usage of SAR sensors for monitoring the marine environment.

1. INTRODUCTION

With the coming of simultaneous flight operations of three calibrated spaceborne Synthetic Aperture Radar (SAR) systems (ENVISAT, RADARSAT-2 and ALOS) employing wide swath (~500km), multi-frequency and multi-polarization technology, SAR application will be on the threshold of a new era. Add to this the more focused satellite systems being planned by individual countries (ESA’s TerraSAR-L, Germany’s TerraSAR-X, Italy’s Cosmo-Skymed, and Argentina’s SAOCOM) and we find that we are entering a period where the availability, coverage, and diversity of SAR data will be unprecedented throughout the world.

After ten years of research into estimation of environmental information from spaceborne imaging SAR, now is the time to demonstrate the operational capability of such systems to monitor the marine environment. As will be clear from this summary and the papers in this volume, many of the tools are in place and much of the research and applications are mature, and as is clear above, data availability has never been better. If we do not successfully demonstrate operational capabilities within the next few years, the opportunity to build a sustainable international user base in support of imaging SAR systems for marine monitoring will be lost.

To do this will require international collaboration to facilitate data access and to allow the development and harmonization of uniform systems operating simultaneously at different regions around the world. Such uniformity will be essential to build an international user base that is familiar with a standard set of SAR-derived marine environmental products, is familiar with standard methods to access the products, and routinely uses the products in operational systems. Such standardization is required to make imaging SAR truly an asset for operational marine monitoring.

The first step along this path is to get a snapshot of the current state of the art in operational marine monitoring with spaceborne SAR systems. Four years ago the 1st Workshop on Coastal and Marine Applications of Wide Swath SAR was held at the Applied Physics Laboratory in Laurel MD where researchers from facilities around the world presented a summary of the then emerging technologies for utilizing wide-swath SAR imaging systems for coastal and marine applications (Beal & Pichel 2000). The 2nd Workshop on Coastal and Marine Applications of Synthetic Aperture Radar was held in Svalbard Norway on 8-12 September 2003. The second workshop was specifically focused on providing an overview of the operational tools now available within the international community, the new methods and applications that researchers were pursuing, and the future directions that marine applications may go. This proceedings provide that state of the art summary from the 2nd coastal and marine SAR applications workshop.

This second workshop focused on answering three questions: (1) What progress has been made since the first workshop on operational SAR marine applications; (2) What are the currently available tools for deriving marine environmental products and what validation results have been performed; and (3) What are the future directions for marine monitoring. Instead of the traditional approach of allowing individual researchers to present summaries of their work, it was decided that to facilitate answering these questions the workshop would be divided into four applications areas: Winds, Waves, Sea Ice, and Currents & Features. For each application community and workshop participants prepared a single summary.
presentation of the state of the art in that application area, addressed these questions, and in the process came to a consensus as to the answers. In this proceedings are four summary papers from each application which resulted from these presentations and were contributed to by all the researchers attending the workshop. Following the summary papers are shorter technical papers submitted by individual researchers discussing their particular application or technique in more detail.

There are of course other applications areas where SAR imaging plays a role, three of particular interest being ship monitoring, oil spill detection, and shallow water bathymetry. The former two areas are currently being addressed in two European programs, the OCEANIDES project and the Detection, Classification and Identification of Marine Traffic from Space (DECLIMS) project. Both of these projects will shortly provide state of the art reports on these applications, and so it was decided not to duplicate their efforts in these proceedings.

Sections 2 and 3 of this paper provide an overall summary of the workshop answers to the questions posed above. These answers are drawn from results generated by all the researchers working internationally in these applications areas, and as such they are all co-authors to this summary. The four summary papers as well as the detailed technical papers that are in these proceedings provide the background, references, and details to support the conclusions we state here. We refer the reader to the other papers in these proceedings and to the summary papers in particular. Section 4 provides the author’s view of the next steps toward operational SAR usage, and Section 5 presents a summary and discussion.

2. WHAT PROGRESS HAVE WE MADE OVER THE LAST FOUR YEARS

An important question addressed in this second workshop was to summarize what progress has been made in operational use of SAR since the first workshop. That first workshop focused on emerging technologies and initial demonstrations of utilizing SAR images to manually derive information. Out of the second workshop it became clear that a large body of work has been ongoing to make a number of these applications operational, to incorporate SAR imagery routinely in some operations, and to continue to develop new approaches for estimating marine environmental information.

In the estimation of winds, the accuracy of the extracted wind speeds and directions has been documented over the last years by comparison to $in situ$ buoy observations, winds derived from satellite-based scatterometer sensors, and model winds by a wide range of researchers [Vachon & Dobson (1996), Wackerman et al. (1996), Fetterer et al. (1998), Horstmann et al. (1998), Kerbaol et al. (1998), Korsbakken & Furevik (1998), Korsbakken et al. (1998), Lehner et al. (1998), Mastenbroek (1998), Monaldo et al. (2001), Thompson et al. (2001), Furevik & Korsbakken (2000), Horstmann et al. (2000), Horstmann et al. (2000b), Lehner et al. (2000), Monaldo et al. (2001), Thompson et al. (2001), Furevik et al. (2002), Wackerman et al. (2003)]. These new results support that wind speeds can be derived operationally from SAR imagery with errors (in the sense of a root-mean-squared-error, RMSE) of less than 2 m/s and with spatial resolutions of a few kilometers. This is whether wind directions are derived from the SAR image itself or are taken from scatterometer or model data. Wind directions can be derived from SAR imagery directly with RMSEs of 25 degrees over spatial resolutions of 10 to 25 km [Wackerman et al. (1996), Fetterer et al. (1998), Korbakken and Furevik (1998), Vachon and Dobson (2000), Horstmann et al. (2002), Du et al. (2002), Fichaux and Rachin (2002)]. Over the past two years, operational delivery of wind fields (as well as ship location maps) from SAR imagery in under 3 hours has been routinely demonstrated as part of the NOAA/NESDIS Alaska SAR Demonstration Project (Pichel & Clemente-Colon, 2000), getting the system significantly closer to delivery times that weather forecasters require (often within 2 hours). Fig. 1 shows an example wind field product that is automatically generated as part of this project and that combines results from two different algorithms. In addition, the wind fields being derived in the Alaska SAR Demonstration are being used to determine ferry routes around Alaska, and have been used in NATO exercises. Finally new techniques for wind estimation from SAR continue to be developed; utilizing the smearing effects in SAR to estimate wind speed and the cross-spectrum to derive wind vectors [Egen et al. (1998), Kerbaol et al. (1998), Lehner et al. (2000)].

In wave estimation, the use of SAR images (mostly imagettes; 5 km X 10 km SAR images acquired every 100 to 200 km along the satellite orbit) to estimate wave spectra is now running operationally at a number of meteorological offices (The Met Office UK, Meteo France, Norwegian Met Office, and the European Centre for Medium-range Weather Forecast (ECMWF)) (Lotti et al. 2003) using tools based on transfer functions between SAR image modulations and wave height modulations [Hasselmann & Hasselmann (1991), Krogstad et al. (1994), Egen & Johnson (1995)]. Fig. 2 shows an example of such a spectrum that was derived by DLR from ERS-2 imagery processed to simulate ENVISAT data and...
compared to what was available previously, the ERS UWA Spectrum. The new approaches can estimate wave direction (via the spectrum of the imaginary part) whereas the previous approaches had a 180 degree ambiguity. Over the past years a number of programs have been performed to compare SAR derived spectral parameters to those generated from global wave models (mainly WAM) [Bruning et al. (1994), Heimbach et al. (1998), Lehner et al. (2000)]. RMSE in significant wave height of 0.4 to 0.6 m, in wave period of 1.2 s, and in wave direction of about 20 degrees have been established in a range of experiments. Finally, new techniques for deriving wave spectra from SAR imagery continue to be developed, and in particular techniques that utilize a more accurate non-linear transfer function are currently being tested, as are the possibility to derive individual wave and wave group parameters [Matstenbroek & Falk (2000), Schulz-Stellenfleth & Lehner (2001), Schulz-Stellenfleth & Lehner (2003a), Schulz-Stellenfleth & Lehner (2003b), Dankert et al. (2003)].

Fig. 1: Example of a wind field product. The wind speed values in color are from the JHU/APL algorithm using model wind directions shown as the large arrows located at the grid line intersections. The smaller arrows embedded in the wind image are from the General Dynamics algorithm. For both, color represents the estimated wind speed.

Fig. 2: Example wave spectrum product generated by DLR (bottom left) that comes from the complex-valued imagettes compared to a product using previous methods (right). The image (upper left) comes from the ERS-2 sensor and was processed to simulate what ENVISAT produces. Note that the old methods did not indicate wave direction whereas the complex-valued imagettes can generate wave direction via the spectrum of the imaginary part. Figure courtesy of Susanne Lehner, DLR.
In sea ice monitoring, over the past years operational use of SAR imagery to manually derive sea ice type has grown from two centers in 1999 to a number which now include centers in the United States, Canada, Denmark, Finland, Germany, Sweden and Norway [Wohl (1995), Vainio et al., (2000), Bertoia et al., (1999)]. SAR imagery is now fully integrated into operational data analysis and product generation at these ice centers is being used routinely to validate ice edge information derived from QuickScat scatterometers and SSM/I radiometers and to help determine ice type. As an example, Fig. 3 shows a RADARSAT SAR image that was utilized to help develop the ice edge information shown in the attached Canadian East Coast ice chart. Techniques for using SAR imagery to track drifting ice and to estimate ice deformation have recently been utilized by the ice centers as experimental products [Kwok et al (1990), McConnell et al. (1991), Williams et al. (1999)]. New techniques in this field are also being developed, including the use of polarimetric SAR data for ice classification and ice edge locations. However, automated tools for deriving ice information from SAR imagery were identified in the workshop as an important area for ongoing research in the sea ice community [Havercamp et al. (1995), Havercamp & Tsatsoulis (1999), Soh & Tsatsoulis (1999), Weber et al. (2003), Soh et al. (2004)].

Estimating currents from SAR imagery, as well as exploiting other oceanic features, is perhaps the most research-dominated application area addressed by the workshop. Most of the work over the last years has been in development of improved forward models to predict the SAR signatures of regions with changing oceanic currents [Romeiser et al. (1997), Romeiser & Alpers (1997), Johanessen et al. (1996), Jansen et al. (1998), Chubb et al. (1999), Romeiser & Ufermann (2001), Vogelzang (2001), Kudryavtsev et al. (2003a), Kudryavtsev et al. (2003b)]. Fig. 4 shows an example output from one such model, comparing actual radar cross section perturbations across a current front to simulated values. However, operational manual image analysis has become incorporated recently for a number of users, including the Norwegian Navy for locating fronts and tracking oil, the UK Hydrology Office for locating current fronts and internal waves, and the Brazilian oil company Petrobras for tracking oil spills and locating oil seeps. In addition, new techniques for estimating currents based on the Doppler shift in complex-valued SAR imagery are being pursued, as well as the use of along-track interferometric SAR systems for direct observations of surface currents.
Overall, the workshop successfully focused attention on a large amount of work that has been ongoing recently to make SAR marine monitoring more operational. Perhaps more importantly, it also identified a wide range of applications that now routinely utilize SAR imagery in generating products both automatically and manually.

3. WHAT TOOLS ARE CURRENTLY AVAILABLE

A second focus of the workshop was to identify what tools are currently available for extracting marine environmental products from SAR imagery. Clearly, for SAR systems to be operational in marine monitoring, a standardized set of tools for deriving information will need to be established and made available to the community. In fact, as discussed below, demonstrating such a uniform set of tools will be the next step in the path to achieve fully operational utility. For details concerning all of these tools, please see the accompanying summary and detail papers.

In wind vector estimation, a wide range of tools are now available with various degrees of user interaction required, including codes from the German GKSS Research Center, the Canadian Center for Remote Sensing (CCRS), the Norwegian KSAT, the Norwegian Nansen Environmental and Remote Sensing Center (NERSC), the French Boost Technologies, General Dynamics in the U.S., the John Hopkins University Applied Physics Lab in the U.S., the German Aerospace Center (DLR), and the European Space Agency (ESA) [Wackerman et al. (1996), Kerbaol et al. (1998), Korsbakken et al. (1998), Mastenbroek (1998), Horstmann et al. (2000a), Lehner et al. (2000), Monaldo et al. (2001), Vachon and Dobson (2000), Horstmann et al. (2002), Du et al. (2002), Fichaux and Rachin (2002)]. Some of these tools estimate wind speed and direction, some estimate just wind speed.

In wave estimation, a number of institutions have automated tools to generate wave spectra from SAR image spectra. The Max Planck Institute algorithms (MPI-1 and MPI-2) are the ones currently running at the meteorological centers (ECMWF, Meteo France, The Met Office UK) [Hasselman & Hasselman (1991), Krogstad et al. (1994)]. In addition there are a range of tools requiring differing forms of inputs (e.g. some require an a priori wave spectrum and some do not); a European Space Agency (ESA) algorithm developed by NORUT and IFREMER (usually referred to as the ESA algorithm) (Egen and Johnsen (1995)), an algorithm from ARGOSS called the Semi-Parametric Retrieval Algorithm (SPRA) (Mastenbroek & Falk (2000)), two algorithms from DLR called the Partitioning Rescale and Shift Algorithm (PARSA) and one referred to as LISE (Schulz-Stellenfleth & Lehner (2003)), and an algorithm from General Dynamics (Lyzenga (2002)). All of them have been compared against combinations of WAM predictions and in situ observations to varying degrees and have reproduced significant wave heights with RMSEs of 0.4 to 0.6 m, dominant wave periods with RMSE of 1.2 s, and dominate wave directions with RMSEs of 20 degrees.

In sea ice monitoring, most of the tool development to date has been on user interactive tools for helping the ice analysts provide sea ice maps operationally, and these are utilized at all of the international ice centers currently [Wohl (1995), Vainio et al., (2000), Bertoia...
et al., (1999)]. The exceptions to these are tools developed by Jet Propulsion Laboratory (JPL) to automatically determine ice deformation over time in the Arctic and automatically track ice motion (both part of the Radarsat Geophysical Processing Station (RGPS) running at the Alaska SAR facility) [Kwok et al., (1990)]. None of the automated tools have yet been validated in the sense of generating RMSEs for specific environmental quantities, although as was noted above a major thrust for the sea ice community is the automation of more monitoring tools [McConnell et al. (1991), Havercamp et al. (1995), Havercamp & Tsatsoulis (1999), Soh & Tsatsoulis (1999), Williams et al. (1999), Weber et al. (2003), Soh et al. (2004)].

In estimation of currents and other oceanic features, multiple models are being developed to generate SAR signatures from descriptions of the underlying environmental parameters with four models having reached a level of maturity: the ERIM Ocean Model developed by what is now General Dynamics [Lyzenga and Bennett (1988)], the model developed by the University of Hamburg [Romeiser et al., (1997), Romeiser & Alpers, (1997)], the Radar Imaging Model (RIM) model developed by Nansen International Environmental and Remote Sensing Center (NERSC) [Krudryavtsev et al. (2003a), Krudryavtsev et al. (2003b)], and the ARG OSS model [Vogelzang (2001)]. All of these are still research codes that contain different physical assumptions to explain SAR signatures observed in various experiments. Automated algorithms have also been developed recently to help users interpret image features, including the Bathymetry Assessment System (BAS) by ARG OSS [Calkoen et al. (2001)] as well as algorithms for automatically locating oceanic features in SAR imagery using wavelet analysis [Rodenas &Garello (1998), Wu & Liu, (2003)]. Tools to locate and characterize ocean features have also been developed and or refined under the MARSAIS project [Johannessen et al. (2001)]. Tools which require some user interaction are estimations of currents using the Doppler centroid shift in complex-valued SAR imagery (developed by Boost Technologies) and estimation of internal wave parameters by the University of Hamburg.

In summary, the range of tools available for estimating coastal environmental parameters has significantly increased over the last few years. A number of the tools are automated (including estimation of wind vectors, wave spectra, ice deformation, near-shore bathymetry, location of current features and ship detection) whereas a number of the tools still require some level of user interaction (including other wind vector tools, ice type classification, current gradients and radial currents, and oil spill detection). Perhaps more importantly for operational use, the environmental products are starting to be validated (i.e. generating RMSE values) against in situ observations and/or models. The most heavily validated to date with in situ observations are the wind vector tools. The wave spectra tools have been validated against some in situ observations but mostly compared against model results. However a number of validation campaigns with in situ observations are either on-going or being planned. The remaining tools are less mature in their development cycle and thus have not yet been validated to the level of the winds and waves tools, but a number of them, estimation of currents in particular, are just coming into validation studies. Overall, the tools that exist right now already span a large range of the coastal environmental parameters desired by users.

4. WHERE DO WE GO FROM HERE

The 2nd Workshop on Coastal and Marine Applications of SAR has successfully provided a snapshot of the current state of the art in coastal monitoring from SAR systems. Although not specifically addressed in the conference, it is important to also understand where the community could go from here to continue the growth of operational usage of SAR sensors. The authors of this overview paper propose that the next step on the path to achieving operational capability is to provide an international demonstration of environmental products generated from SAR sensors at a range of locations. This demonstration must show uniformity in product generation from all sites, and post all products on the internet for interchange between partners. The tools would be run operationally at each location to demonstrate the timeliness and performance of the products to local users, based on the models of the ongoing NOAA/NESDIS Alaska SAR Demonstration Project which automatically posts wind vectors and ship locations usually within 3 hours of data acquisition, and the Norwegian quasi-operational system for oil spill detection, ship locations and wave retrieval. We envision that the tools would be drawn and integrated from a range of international partners and taken from the set of tools described above, using the most robust approach for each product. Such a demonstration would verify the capability of SAR sensors to provide uniform, world-wide, coastal products, determine the timeliness of the product generation, and validate the performance of the products.

We envision the demonstration lasting for one year, from mid-2004 to mid-2005. The tools that would be used to generate products would fall into two types; automated and user-interaction. It is clear that the automated tools currently available would include: (1)
wind fields; (2) wave spectra (include parameters derived from the spectra); (3) ship locations; and (4) ice deformation. The user-interaction tools would include locating current fronts and generating ice type maps. The products from each tool would be standardized, so that all locations would generate the same format for wind fields, wave spectra, etc. Since NOAA/NESDIS in the U.S. and Nansen Environmental and Remote Sensing Center in Norway are running demonstrations off the coasts of Alaska and Norway, respectively, we envision at least starting with these locations, with the possible early additions of locations off the coasts of Florida, Great Britain, and France, since all of these locations have some form of image download capability and are generating some form of products now from SAR imagery. Over the course of the demonstration, other sites could be added.

Operational access to SAR imagery will be an issue for such a demonstration, even though the number of satellites flying could be unprecedented. Under existing cost structures such a demonstration may not be able to afford running for a full year, so it may require special arrangements for access to, and sharing of, SAR imagery among the sites. In addition, although a number of satellites may be available, it is not clear what the duty cycle for each will be, and most importantly how much of that cycle could be devoted to coastal applications. It would be ironic indeed to have more satellites than ever before with less marine collections than ever before.

With the results from such a demonstration in hand however, it would be time to connect to the user community, which often requires proof of operational capability before committing to use a product. Although many, if not all, of the marine environmental products currently being generated were motivated by user needs (and in fact many products are being utilized right now by users operationally), it will be essential to actually show that these products can be used. Perhaps more importantly, it will be important to show that these products are useful, and help users get their jobs done better than they would without the SAR products. If we can demonstrate operational product generation, and demonstrate user need and use of the products, we will be well on the way to building the sustainable international user base in support of SAR imaging systems.

5. SUMMARY AND DISCUSSION

We believe that this summary paper and these proceedings validate the claim that the 2nd Workshop on Coastal and Marine Applications of SAR successfully captured a snapshot of the current state of the art on coastal monitoring with SAR systems. Furthermore, we believe that the snapshot shows examples of capabilities that are well on their way to operational levels in winds, waves, sea ice and currents, and that are starting to be validated against in situ observations of the environmental parameters. Finally, we believe that the snapshot also contains a large range of users who right now are utilizing SAR-derived products operationally; including weather services, ferry operators, meteorological centers, sea ice centers, military organizations, hydrographic offices, and industry. In addition, we expect to see a growing need and use of SAR derived products in the context of Global Monitoring for Environment and Security (GMES); the joint ESA-EU initiative that is currently under development with the goal to be implemented for operational use by 2008. However, much progress still needs to be done before we can claim a sustainable international user base for imaging SAR sensors, and we have attempted to outline a path to that goal with milestones along the way.

As the SAR community moves toward operational coastal monitoring, the issue of the re-visit time that any set of imaging radar sensors would be able to attain needs to be considered. Clearly, the number of satellites required for near-real time radar image acquisition over the globe will never be affordable. Rather, it is incumbent on the application providers to differentiate between real-time operations which may never be supportable by imaging satellites (or which will only be supported in certain locations), versus longer-time statistical descriptions of scenes that a few imaging satellites could readily provide globally. This does not kill the idea of an operational SAR monitoring system, but rather constrains the community to pursue users that can be realistically supported by such systems.

The future of marine monitoring from SAR is clearly bright from the researcher point of view, and is clearly being embraced from a subset of users right now. The challenge for the future is to focus the research community to provide uniform, consistent products, and educate the user community how best to utilize these products. Then the argument for sustainable imaging SAR-like sensors can be realistically made.

Finally, plans are underway for the dedicated 3rd Workshop (of what we hope is an on-going series every two years) sometime in 2005. We would anticipate this workshop focusing on user needs and on making the connection between the demonstrated capabilities and helping the users get their jobs performed effectively. Whereas demonstrated operational product generation will be a goal after this 2nd workshop, validating usage of the products would be the goal after the 3rd workshop.
6. REFERENCES


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