FINDINGS OF THE DECLIMS PROJECT – DETECTION AND CLASSIFICATION OF MARINE TRAFFIC FROM SPACE

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ABSTRACT

The 24-partner DECLIMS project aims to establish and enhance the state-of-the-art in operational ship detection from space. Benchmark tests of automatic SAR detection algorithms have shown that existing systems are mature enough to be used operationally, but at the same time still suffer from problems that can be remedied by implementing available knowledge. Existing systems score less well on automatic vessel *classification* in SAR images; more fundamental improvements seem to be needed there. The state of development of automatic ship detection and classification algorithms for *optical* images lags behind that of radar. The characteristics of the satellite-based information (minimum detectable vessel size, area coverage, repeat frequency, etc.) and the way in which it can complement other information on ship traffic dictate the level of acceptance and maturity in the various application areas, ranging (in decreasing order) from fisheries control, via defence, pollution control, and maritime security, to traffic control. These application areas pose different requirements on future sensors; those from fisheries control are discussed in some detail.

1. PURPOSE OF DECLIMS

The DECLIMS project aims to establish the state of the art in detection and classification of maritime traffic from space, and to be a focus for research in that field. The project, partially funded by the European Commission, brings together 24 actors and stakeholders in satellite ship detection and classification, from a variety of backgrounds: small and large industry, institutes and academia; civilian and defence; from within the EU and outside. The project partners are listed in Fig. 1. Imaging sensors are considered, both optical and radar. The project started May 2003 and is planned to last 3 years. This paper intends to give a brief summary of the main findings of the project so far. The discussion is divided into optical results, radar results, users, data fusion and needs for future sensor systems. The primary interest is in the operational status of the methods, and less in theoretical or exploratory possibilities: what can really be done today with space-based earth observation sensors for maritime surveillance?

2. OPTICAL

Although present-day high and very-high resolution optical images readily show ships and indeed reveal a lot of information about them, ship detection and classification from optical images is much less developed than from radar images. This is a consequence of the novelty of the very-high resolution optical satellite sensors, the problem with clouds, and the fact that the swath of very-high resolution imagery is relatively small making it less suitable for surveillance over the oceans. In optical images of 2.5 m resolution or better (such as SPOT-5, EROS, IKONOS, QUICKBIRD), ships are easy to detect with the human eye, their size is readily estimated and details on the superstructure can easily be discerned. Some of the larger vessel types can be immediately recognised, such as container ships, oil tankers and bulk carriers. Intermediate vessels still show details, but their interpretation is not so

Fig. 1. The partners of the DECLIMS project: Joint Research Centre (European Commission); QinetiQ (UK); CCRS, Defence Canada, MDA Geospatial Services (Canada); CEDRE, CLS, IRD, SPOT Image, BOOST Technologies (France); TNO (Netherlands); IXL, Definiens (Germany); FMA-LaMMA (Italy); FFI, Kongsberg Spacetec, KSAT (Norway); Doxiades Geoimaging (Greece); Institute of Remote Sensing Applications (China); Absolute Communications, General Dynamics-AIS (USA); Mitsubishi Heavy Industries (Japan); ESA; Universitat Politecnica de Catalunya (Spain).

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straightforward: it is difficult for an untrained interpreter to discern e.g. a fishing vessel from a patrol boat. Small (< 10 m) vessels are still detected but their classification is impossible. A good guess can be made using context information, e.g. the nearness of a marina indicates that a small target is likely a pleasure boat, but this approach is less useful if the purpose is to detect threats or illegal activities.

In the DECLIMS group, only three partners are actively involved in optical ship detection, as opposed to 15 in radar, and this seems to reflect the global situation. The immaturity of optical vessel detection is underscored by the fact that capacity for *automatic* vessel detection (and classification) from optical images is very limited. In addition to the reasons mentioned above, this may also be a consequence of the increased complexity of detecting ships in optical images, where shapes, segments and contrasts need to be taken into account, as opposed to the radar case which is ultimately simply based on the detection of a bright pixel. There is a preference for panchromatic imagery over multi-spectral – more bytes (bandwidth) of information is better spent on increased resolution than on additional colour.

To make a fair comparison between ship detection capabilities in radar and optical, one would have to compare at the same resolution. For ship detection, resolutions used range from 150 m (ENVISAT ASAR Wide swath, only for large merchant ships) via 50 m (RADARSAT ScanSAR) and 25 m (ENVISAT ASAR Image and Alternate polarisation modes, RADARSAT Standard) to 8 m (RADARSAT Fine). While the 50 and 25 m radar resolutions are extensively used for ship detection, these resolutions have not at all been used for ship detection in the optical, presumably because performance is not adequate. On the other hand, *classification* in radar images is much more difficult than in optical ones. This paper (section 3.2) will demonstrate that statement for 25 m and 8 m resolution; and on the basis of airborne SAR images it is known that also at meter resolution, classification and recognition of radar targets is more difficult than in the optical. The conclusion therefore is that radar (at medium resolution) is most suitable for ship detection, whereas (very) high resolution optical is most suitable for ship classification. One exception may be small wooden and plastic boats which can be difficult to detect with radar but (depending on their colour) can be found in the optical.

3 RADAR

3.1 Detection

In 2004 a benchmark test for SAR ship detection was run, which consisted of having 8 different systems analyse the same set of 17 SAR images and comparing the detection results. The outcomes were reported in [1]. Of the 8 detectors, 6 were operational (i.e., being used for customers) and 2 experimental. The operational systems rely on detection of pixels with a high value compared to the local background statistics (CFAR approach), sometimes employing a template to match expected target shape. Experimental systems use approaches based on wavelets [2] and sub-aperture cross-correlation. It was found that the operational systems, although performing markedly different on individual images, had an overall comparable performance. (The test set included images with various resolutions, modes, vessel sizes and weather conditions.)

SAR vessel detection, being essentially a process of finding bright pixels on a noisy background, is a random process characterised by a detection probability and a false alarm rate. While users may accept that, they at least want to know how large these two numbers are on a case-by-case basis, e.g. to better be able to decide on follow-up actions. Unfortunately it is still difficult to make a good estimate of these numbers, due to the many factors that influence the detection outcome. The DECLIMS benchmark test showed a >85 % detection rate on all but the most difficult images, but in fact the test set is too small for good statistics. Experience of JRC on detectability of fishing vessels, analysing almost 900 known fishing ship positions in 100 images, indicate a detectability of 80 % for larger fishing vessels (45 m on average) in RADARSAT ScanSAR Narrow B images (50 m resolution) and over 90 % for somewhat smaller fishing vessels (35 m on average) in RADARSAT Standard images (25 m resolution) [3]. Less work has been done with ENVISAT ASAR, but the available experience indicates a similar performance of its Image mode (25 m resolution) to RADARSAT Standard. ENVISAT's Wide swath mode at 150 m resolution however is not suitable for detection of fishing vessels.

The 2004 SAR vessel detection benchmark test indicated a number of specific problems common to all or most of the systems. These problems can be categorised in two groups. First, problems of which the solution is known but simply not implemented in the automatic detection systems (presumably because the investment is too large). Second, more fundamental problems for which a realistic solution is not (yet) available. In the first category, we find problems with the coast line, azimuth ambiguities and side lobes. Concerning the coast line, a land mask needs to be placed on the image to prevent detections on land. Problems arise due to inaccurate (real-time!) geolocation of the satellite image, inaccurate or outdated (due to coastal construction) land masks, and intertidal areas. Solutions can be found in real-time matching of the land mask with the coastline as found in the image, dynamic updating of land masks and special consideration of intertidal areas, possibly even taking into account predicted water levels. Azimuth ambiguities (often due to strong scatterers on land, but also from strong maritime targets) and side lobes (especially in Fine beam images where the backscatter from one resolution element can become extremely high) give rise to false alarms. However, they represent known and quantifiable effects that can in principle be compensated for. The second category of more fundamental problems includes azimuth smearing due to vessel motion on the waves, the occurrence of multiple nearby peaks and sea surface features. Azimuth smearing is possibly not so much an obstacle to detection, but it obscures a vessel's real size and heading. Multiple nearby peaks are regularly found to coincide in the SAR image with a single known small vessel position. In such a case it is difficult to say whether these peaks indicate two distinct targets, or result from separate scatterers on the same target (possibly separated in azimuth due to motion effects). This is a problem, because often the radar data are gathered in the first place to count ships and establish the presence of unknown ships. Finally, apart from the distributed clutter, the sea surface can show localised features of increased brightness due to a wide variety of geophysical causes. Some of them are difficult to distinguish from real targets.

In 2005, another benchmark was executed, primarily aimed at classification, but of course detection was performed in the process. The classification results will be discussed in the next section. Concerning detection, several of the participants had ameliorated the performance of their system by incorporating improvements based on the outcomes of the first benchmark. Innovative solutions make use of absolute radar backscatter values to discriminate certain low wind speed-related sea clutter features from targets, and advocate the use of sub-apertures to recognise ambiguities [4]. However, many of the common problems noted above were still in existence.

3.2 Classification

Users of ship detection systems want to know what type of ship is detected. Unfortunately this is very difficult to derive from present-day satellite radar images. Apart from an incidental attempt, none of the systems run by the DECLIMS project partners provides this information; output on vessel classification is limited to size estimates. In the 2005 benchmark on SAR vessel classification, 9 systems participated. The systems and their types of outputs are listed in Table 1. Although of course not all existing SAR ship detection systems are included, DECLIMS does represent a significant part of them. It can be seen that almost all systems give a length estimate, fewer also give a width and heading estimate, and even less an estimate of the RCS. No system provided all these items. (Note that the systems are evolving and capabilities are steadily increasing.)

Table 1. Automatic vessel detection systems used in the DECLIMS classification benchmark and the type of output they give (in addition to detected target position). "Reliability" is an indication of the reliability of the detection. RCS is radar cross section.

System	Run by	Reliability	Length	Width	Heading	RCS
SUMO	JRC	x	x	x	x	
MaST	QinetiQ		x	x	x	
FFI	FFI		x	x	x	
GD-AIS	GD-AIS	x	x	x	x	
KSPT/FFI	KSAT		x			
BOOST	BOOST	x	x	x	x	
IAPro	DRDC	x	x			x
OMW	DRDC	x	x			x
VUSAR	DRDC	x				x

The SAR vessel classification benchmark consisted of having these 9 systems analyse 20 images (ERS-2, ENVISAT ASAR Image and Alternate polarisation modes, RADARSAT Standard and Fine). Within the images were 130 ships of known size. Analysis of this benchmark test is currently ongoing and results presented here are preliminary. The vessel sizes (lengths and widths) as output by the various systems were compared with the real ("in-situ") vessel sizes but also with vessel sizes visually estimated by a human operator. Before looking at the outcome of those comparisons, it is interesting to look at how the visually extracted sizes compare with the real sizes in the first place. This is shown in Fig. 2, separately for length and width, and for Standard and Fine resolutions.

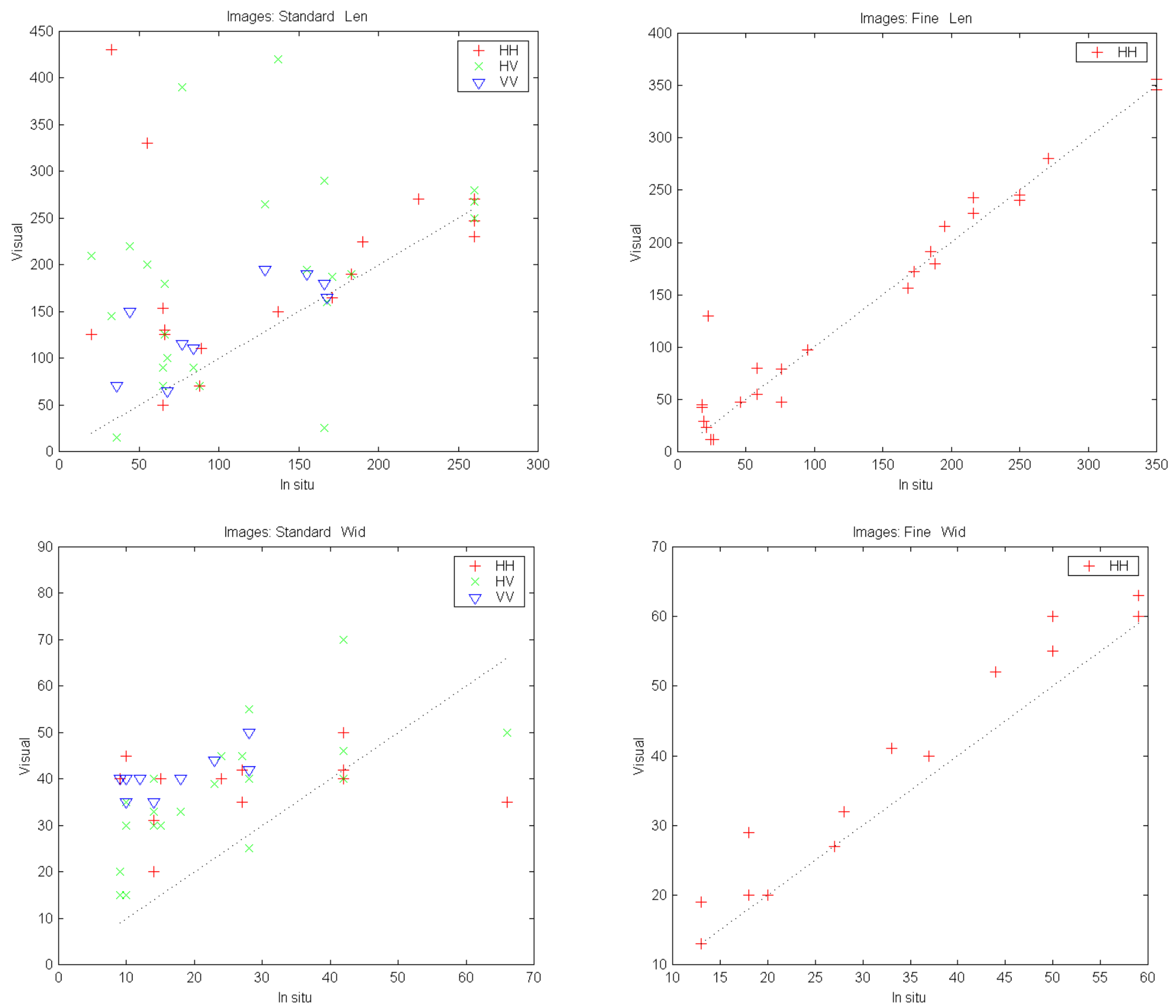

Fig. 2. Comparing visually estimated vessel size to real vessel size. Top row: Length (m). Bottom row: Width (m). Left column: Standard resolution, i.e. 25 m multi-look (ERS-2, ASAR Image and Alternate polarisation and RADARSAT Standard). Right column: Fine resolution, i.e. 8 m single-look (RADARSAT Fine). Symbol shape and colour indicate polarisation.

Fig. 2 (left column) shows that the visual size estimate can be very discrepant from the actual size in 25 m resolution images, in most cases with an overestimation. The visual size estimate from 8 m resolution images (right column) seems to work much better, with some overestimation for the width. Considering that present-day automatic algorithms are not as sophisticated as the human eye, one can hardly expect the automatic systems to perform better. This is borne out by Fig. 3 which plots length estimates from the various ship detection systems against real length.

Plots of estimated against real vessel width are similar to Fig. 3. These results shows that estimating vessel size is for all automatic systems that were tested still quite difficult. The figure also shows a marked underperformance for a few particular systems. As in Fig. 2, the results for the 8 m resolution images (right side) are much better, especially if some outliers are disregarded. (The number of points in the graphs of Figs. 2 and 3 is not the same because not all vessels were analysed by all systems nor visually.)

Finally, Fig. 4 compares system-estimated length to visually estimated length. Also this figure shows considerable scatter, indicating that the automatic algorithms do not provide the same results as the visual analysis, and therefore that the errors in the automatic algorithms with respect to the real values are partially a consequence of inherent distortion in the radar imaging of the ships and partially of not properly analysing the radar signature (assuming that a human operator can properly analyse the radar signature).

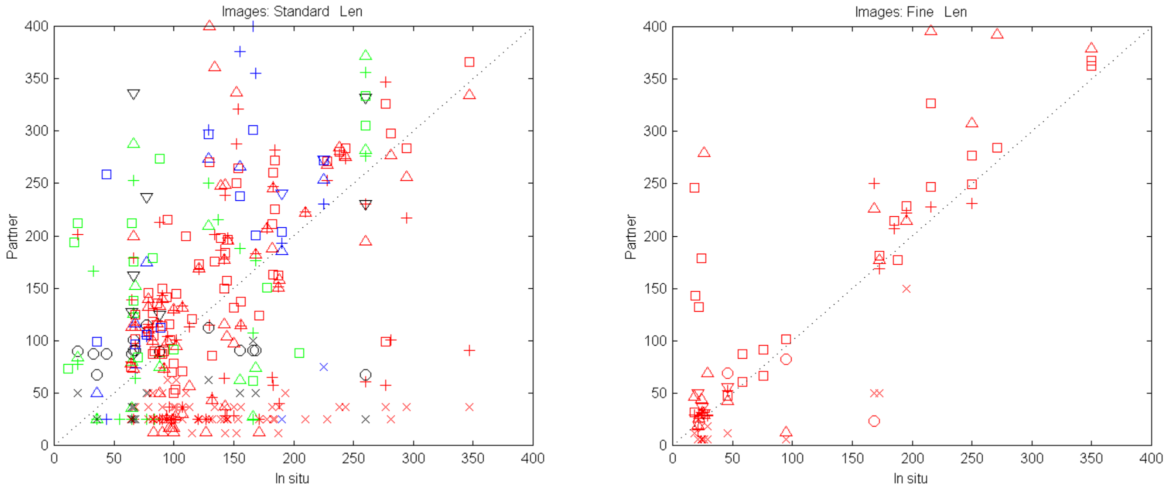

Fig. 3. Vessel length as estimated by the various ship classification algorithms from Table 1 against real length. Left for 25 m multi-look images, right for 8 m single-look images. In this figure symbol shape signifies the algorithm and colour signifies polarisation (HH = red, HV = green, VV = blue, and a composite result from two polarimetric channels = black).

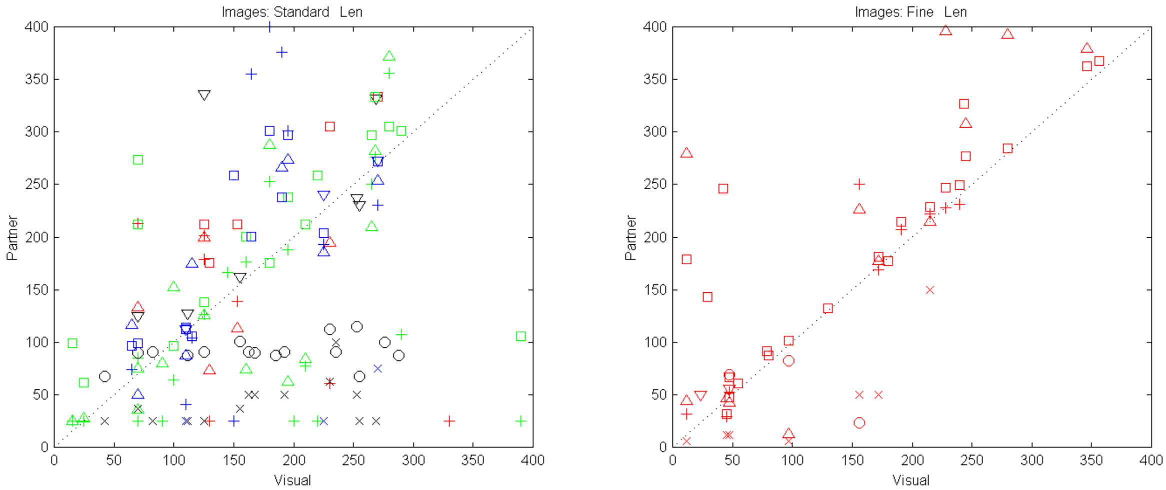

Fig. 4. Comparing automatic systems vessel length estimates to visual length estimates. Legend as in Fig. 3.

From the above, one might conclude that 25 m resolution is insufficient for reliable vessel size estimation and that 8 m is needed. However, it should be noted that in the 25 m graphs (left columns of Figs. 2-4) the size estimates do not improve for the larger ships, which would be expected for a pure resolution effect. On the basis of the present data it is also possible that the difference between Standard and Fine images here is a result of particular image conditions: many of the known vessels in the Fine images were stationary (at anchor).

4 WAKES

Moving ships can show a wake in a satellite image, both in radar and in optical. The wake can give information about the speed and direction of the ship. The DECLIMS project plan called for a benchmark on wake detection. A significant amount of literature has been published on wake generation, imaging and detection in the past 15 years. In spite of that, hardly any of the operational vessel detection systems participating in DECLIMS perform a wake detection and analysis. In the case of optical, the moving vessel and its near wake can be difficult to separate because they are connected and can have similar brightness, so wake and (moving) ship detection often amount to the same. However, the overall immature state of the automatic optical vessel detection algorithms was already noted. For radar, the lack of well-developed wake detection capability is probably linked to the fact that lately most of the operational ship detection applications have used RADARSAT (HH) at shallow incidence angles. This configuration which is optimal to detect ships but rather unsuited for wake imaging. Indeed, ship wakes are a rarity in these RADARSAT images, whereas in ERS images (VV, steep incidence) they are more the rule.

As a consequence, no benchmark test on wake detection was performed. It must be concluded that operational capability at present lags behind theoretical capability in this area.

5 USERS AND DATA FUSION

Present and potential users of satellite ship detection include, more or less in order of maturity of the application:

- Fisheries control (finding illegal fishing vessels);
- Defence (maritime situational awareness);
- Pollution (oil spills);
- Civil maritime security (smuggling, trafficking, piracy, terrorism);
- Maritime traffic safety (compliance with traffic rules, collision avoidance).

Generally speaking, information on vessel traffic provided by satellite images is only very limited. Data is available not continuously but only at one instant; within a limited swath; with limited resolution; and with limited detection probability and classification potential. For these reasons, satellite imagery is almost never used on its own for vessel detection applications, but rather in combination with other data sources. For fisheries control, vessel positions from satellite imagery can be combined with positions obtained from VMS, the Vessel Monitoring System [5, 6]. This system of ship-borne transponders is used by the authorities of participating states to keep track of their fishing fleets. VMS positions are submitted (bi-) hourly, or alternatively they can be "polled" on request within a 15 minute interval. Fusion therefore entails interpolating VMS positions from before and after to image acquisition time, and it also has to deal with positional uncertainties both as a consequence of this interpolation and related to (real-time) image geocoding [7].

Vessel detection in the context of pollution applications is helped by correlating with AIS positions. AIS, the Automatic Identification System, is an IMO-regulated transponder system on the larger vessels primarily for traffic safety [8]. By deploying a coastal receiver and linking it to a transmission facility or network, AIS positions can be made available in real-time from within the line of sight of the coastal station (e.g. to 40 km away). The combination of a SAR image, showing both oil pollution and vessels, and AIS data can be an aid to identifying the polluters.

Defence and maritime security applications often amount to alerting for the presence of unknown targets, that may pose a threat. The approach to do this is to combine the satellite targets with vessel positions known from other sources, and it becomes important to use all available sources – AIS, VMS, coastal radar, airborne patrol, etc. This leads to the establishment of a maritime surface picture. A simple example is shown in Fig. 5.

It is the characteristics of the satellite data that dictate the order of maturity of these applications. The snap-shot nature of the satellite lends itself well for combination with the more continuous VMS data to constitute a second tier in the control for illegal fishing. Pollution control is hampered somewhat by the non-continuous nature of the satellite monitoring, but as the lifetime of oil spills is relatively long it is still a viable tool. To find smugglers and the like is already much more difficult because these vessels are often small and fast – consequently the maritime security application is only embryonic. Maritime traffic safety finally is probably the furthest away from reality, because there continuous surveillance is needed, and in addition other systems are already in place (AIS, VTS).

6 REQUIREMENTS FOR FUTURE SENSORS

Based on the experience of using the existing sensors in trying to cover the user requirements, it is useful to make an attempt to identify shortfalls in the existing capacities and formulate requirements for future sensors. Such an exercise must be done for each of the applications separately, because their detailed requirements can be quite different. Here the discussion will be limited to fisheries control. In fact even this is still too wide an application: it has to be split into fisheries control for open ocean and for coastal seas, as these regions have markedly different requirements. (Some users even advocate a split into three: coastal, EEZ and High Seas.) The requirements are formulated in terms of resolution, swath width, revisit time, incidence angle, etc. It is not possible to give hard limits for each of these parameters for two reasons. First, because ship detection is a probability process with detection success depending on many factors. Secondly, because the target vessels have a wide range of sizes, and the smallest ones will always be difficult to detect. Both reasons mean that an improvement in a system parameter will not mean the difference between full failure or full success, but will lead to a proportional increase in performance. On account of this, Table 2 attempts to formulate the requirements by giving two values: one minimal requirement, and one target requirement which would lead to a significant and welcome improvement in performance.

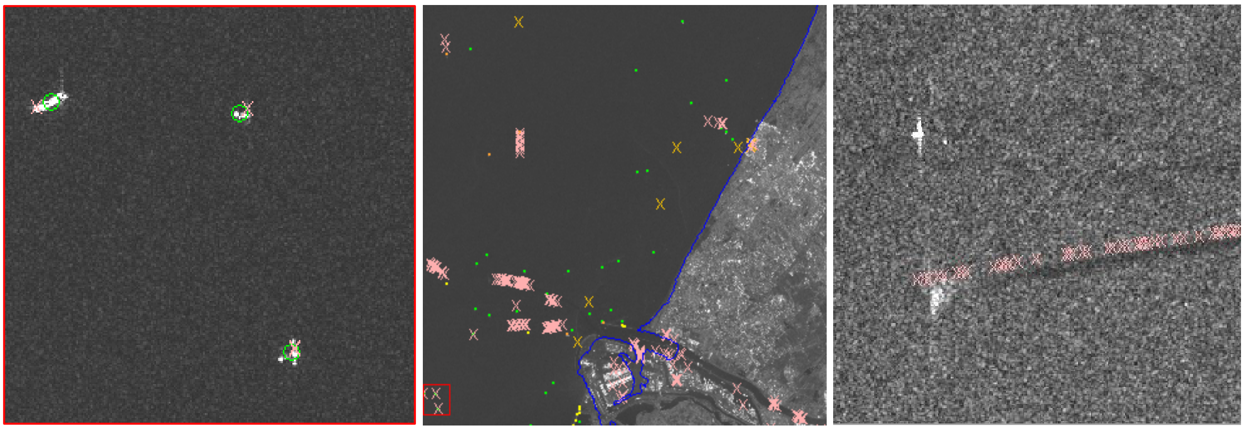

Fig. 5. North Sea coast near Rotterdam harbour mouth, The Netherlands. Satellite targets are green circles, VMS positions are yellow crosses, AIS positions are pink crosses. Centre, a 30x30 km subset from a RADARSAT Fine2 image. The left shows an enlargement with three vessels detected on radar and AIS. The right shows part of another image (RADARSAT Standard5) in the same area. The AIS track (crosses) coincides with a dark wake. The bright spot at the head of the wake is white water just behind the ship (a fast ferry). The bright spot up from that is the ship image subjected to an azimuth displacement (of 1.94 km) due to its range velocity. The velocity calculated from this displacement is equal to the vessel speed as given by the AIS: 41 knots. Images © MDA/CSA 2005.

Table 2. Requirements for future SAR sensors for fisheries control.

Application	**Fishery control: Open ocean**		**Fishery control: Coastal & shelf**		**Consideration**
Requirement	**Minimum**	**Target**	**Minimum**	**Target**	
Revisit	3 d	1 d	3 d	1 d	Need to follow the behaviour of (relatively slowly) moving fishing fleets
Delivery delay (after acquisition)	< 1 hr	< 15 min	< 1 hr	< 15 min	Crucial parameter
Polarisation	HH	HH+HV	HH	HH+HV	HV should help in finding a few targets with low HH RCS, and in discriminating vessels from icebergs, although experience is limited. Not enough knowledge available to make use of polarimetric phase information, so only power is used
ENL	3	5	3	5	Comparisons between ENL=3 and ENL=4 products from the same raw data have shown that the latter leads to noticeable improvement in detection rate
Resolution	55 m	30 m	25 m	10 m	A good detection rate is obtained for ship size >≈ resolution. When ship size <≈ 0.5*resolution, detection is practically lost
Minimum instantaneous swath	300 km	400 km	100 km	150 km	Needed to obtain distribution of vessels and fishing fleets, which are (slowly) moving
Incidence	> 30 deg	> 35 deg	> 35 deg	> 35 deg	These numbers for HH. For steeper incidence too much clutter. For HV they could be steeper, but HV alone cannot be guaranteed to perform adequately
Geolocation accuracy	300 m	150 m	150 m	50 m	High accuracy needed near coast for automatic land masking

The numbers in Table 2 derive from the scenarios and their targets. On the open ocean, the fishing vessels are not very small, mostly 35 m and up, but the areas to be monitored are very extended. In coastal or shelf seas, the fishing vessels are smaller, but so are the areas of interest. These considerations dictate the resolutions and swath widths quoted in the table.

The 'minimum' numbers are essentially derived from present-day RADARSAT values. This satellite has proved to be useful for fisheries monitoring, using its ScanSAR Narrow B mode (50 m resolution, 300 km swath) on open ocean, and its Standard mode (25 m resolution, 100 km swath) in coastal waters. The numbers of the 'target' column are chosen to represent a significant improvement without putting unrealistic demands on technology (or cost). However, for several of the system parameters good cases may be made to put stricter figures there. For example, considering the classification performance discussed in section 3.2, a resolution of better than 10 m might be required in order to provide a good size estimate. A better geolocation accuracy might be required to pinpoint individual vessels in a dense fleet.

For most ship detection applications area coverage is essential: the purpose is to find targets without knowing where they are beforehand. Many newly proposed satellite sensors offer additional information in the form of very high resolution or polarimetry; however, nearly always at the expense of swath width. This extra information will increase detection and classification performance, but for most maritime surveillance applications this gain will not outweigh the reduction in swath width.

In addition to the parameters listed in the table, there are a few more which need not be differentiated into the table's four columns. Radiometric accuracy is not critical because the RCS values of ships are very random. (On the other hand, radiometric accuracy is required to extract wind speed from the SAR image; this is very useful in order to have a better idea of the instantaneous detection performance which strongly depends on local wind speed.) Fast tasking of the satellite would be desirable, e.g. to investigate suspect situations as soon as possible or to cancel programmed acquisitions when high sea states are predicted. People have also proposed cross-queuing to follow up on suspect locations detected in a wide area search with a high resolution zoom-in. Technically, this can be effected by beam squinting or by a constellation with a trailing satellite. Finally, operational customers always stress the need that data are inexpensive and rapidly and reliably available. Operational users tend to spend their funds in the most cost-effective manner, and they have other options besides the use of satellite data.

7 CONCLUSIONS

Ship detection from satellite SAR imagery is an operational application that can be performed in near-real time, with detection and false alarm rates that are sufficient for some users and scenarios but need to be improved for others. Its value for the end-users is only attained when the resulting detections are fused with vessel traffic data from other sources, and this is increasingly being done. Vessel classification from SAR data, however, is still difficult; automatic algorithms do not yet always provide reliable size estimates.

The benchmark tests run in the DECLIMS project have made the operational state-of-the-art more clear, and have enabled developers to improve their systems and products.

In several aspects the implemented, operational capabilities lag behind available theoretical knowledge: e.g. in accurate real-time land masking, side lobes and ambiguities, use of RCS values, wake detection and analysis, and for automatic vessel detection and classification in optical images. More fundamental problems are at issue in the azimuth smearing of SAR vessel signatures, hampering classification; solutions might be sought in alternative treatment of the raw SAR data. As these issues are addressed, capabilities will increase. In combination with a broader availability of space-borne systems under operationally and commercially attractive conditions, this will allow also the more demanding application areas to be served.

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