

Requirements for Polarization Combination for Ship Detection in the Barents Sea

T.N. Arnesen^a, H. Greidanus^b, Ø. Hellere^a, T. Eriksen^a and R.B. Olsen^a

^a Norwegian Defence Research Establishment (FFI), P.O. Box, NO-2027 Kjeller, Norway, email: tna@ffi.no, ohe@ffi.no, toe@ffi.no, rol@ffi.no

^b European Commission, Joint Research Centre (JRC), TP 051, Via Fermi 1, 21020 Ispra (VA), Italy, email: harm.greidanus@jrc.it

ABSTRACT

This paper presents the Hopenjupet trial that was carried out in the Barents Sea between April and June 2006. Synthetic Aperture Radar (SAR) images from RADARSAT-1 and ENVISAT were used to analyse how SAR images and cooperative reporting can be combined. Data from the Automatic Identification System and Vessel Monitoring System have been used to identify detected vessels in the SAR images. The paper also identifies gaps that need to be closed to meet operational requirements for monitoring Norwegian waters.

Keywords: Vessel detection, ship detection, cooperative reporting, SAR, AIS, VMS.

1 INTRODUCTION

The requirements for a national capability to monitor Norwegian waters increase with the increasing shipping and fishing along the Norwegian coast and in the Barents Sea. Spaceborne Synthetic Aperture Radar (SAR) has been used operationally by the Norwegian Defence since 1998 to monitor the Norwegian economic and fisheries zones. Radar satellites increase the overview in vast areas and help the operative decision-making process.

In addition to developing new SAR processing algorithms and recommendations for future use of SAR imagery, the Norwegian Defence Research Establishment (FFI) works on evaluation of the potential quality of space-based Automatic Identification System (AIS) services [2],[3]. AIS is a system of shipboard transponders that automatically exchange vessel traffic information for maritime safety, mandated by the International Maritime Organisation on larger vessels. The current feasibility study performed for the Norwegian Space Centre includes conceptual design of a demonstration mission focusing on vessel detection in waters north of

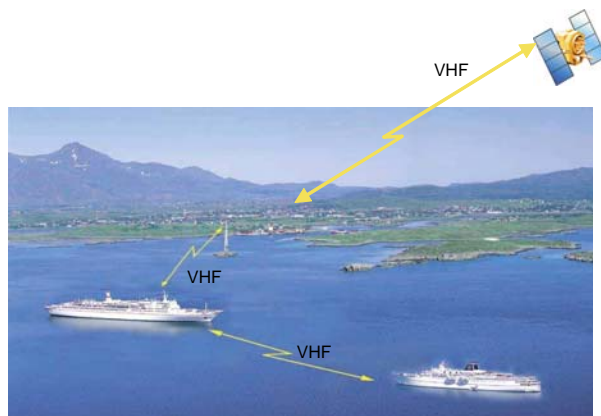


Figure 1. AIS signals sent between vessels and vessels and land. FFI is working on the possibility to have an AIS transponder on a satellite to make it possible to send signals between a satellite and vessels. © Seatex and FFI

the Arctic Circle. This includes an AIS instrument on a satellite. Figure 1 shows AIS signals sent between vessels, as well as vessels and the AIS chain on land. The possibility to have an AIS transponder on a satellite is also shown, opening for the possibility of sending AIS signals between a satellite and vessels.

Operationally, vessel tracking based on SAR and AIS, as well as Vessel Monitoring System (VMS) will give a picture of all vessels in the area. VMS is a transponder system in use for fisheries control by many national authorities. Ship detection in SAR imagery and tracking based on AIS and VMS reports are complementary. SAR, AIS and VMS data can be combined for surveillance in remote areas. AIS and VMS can identify vessels detected in SAR, while SAR can be used to detect vessels not reporting through the AIS and VMS systems. The combination of sources gives the opportunity to unveil vessels that don't send mandatory AIS or VMS reports.

RADARSAT-2, which will be launched in 2007, will offer large flexibility in selection of polarization, incidence angle and resolution. It will have VV-polarization and cross-polarization (HV and VH) channels in addition to RADARSAT-1's HH-polarization. This can lead to a change in preferences and strategy for open ocean surveillance. High incidence angles and HH-polarization have been preferred due to high contrast between the ship and sea. The opportunity to use cross-polarization will probably give better possibilities for detection of ships at lower incidence angles, and gives a new opportunity in ship detection using SAR. FFI and JRC use ENVISAT SAR images to prepare for operational use of RADARSAT-2 and other satellites with multiple polarizations [1]. In this experiment, ENVISAT was used to test how cross-polarization can be used to detect vessels in open sea.

2 HOPENDJUPET TRIAL

Repeated recordings of the same vessels using different SAR modes, polarizations and incidence angles give the ability to evaluate and refine automatic vessel detection algorithms. During the shrimp fishing season in the Barents Sea, fishing vessels are expected to be in the Hopen djupet area (75°N, 30°E), and there is a good possibility to image the same vessels for a number of days. Figure 2 shows a bathymetry map including Hopen djupet. The access to SAR, AIS and VMS data is also good in the area. Nevertheless, the extent of the fishing area is much larger than the 100 x 100 km size of a 25 m resolution satellite SAR image. The locations of the SAR images have to be planned in advance, based on an estimate of where the fishing vessels will be by the time of acquisition. The advance period, related to the image providers' technical capability and pricing schemes, is typically between 3 and 14 days. This introduces the risk that the fishing fleet is missed.

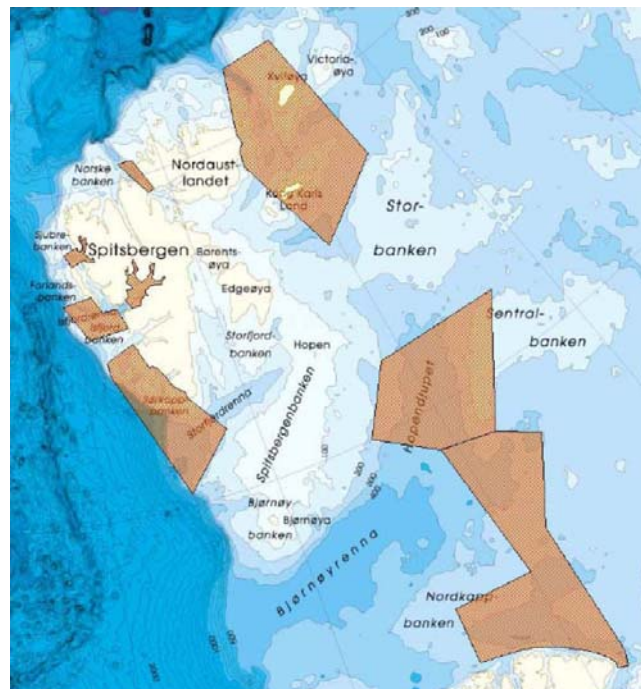


Figure 2. Areas closed for shrimp fishing in April 2005 (shaded). Bathymetry map courtesy of Norwegian Polar Institute.

The goals of the Hopendjupet trial were to:

- Improve knowledge of detection of fishing ships in open sea in SAR.
- Demonstrate how SAR, AIS and VMS data may be used together as cooperative reporting in an operational setting.
- Develop methods and algorithms for fusion of SAR and AIS data in vessel tracking services.
- Contribute to the evaluation and improvement of SAR detection algorithms taking detailed information about the ship, polarization and the incidence angle into account.
- Validate SAR and AIS for research purposes.

Recommendations on which polarization channels might be used to be able to detect vessels most efficiently were also a goal. Analyses to see if two channels are enough for ship detection in open sea were planned.

2.1 The Experiment

The Hopendjupet trial was carried out in the Barents Sea between April and June 2006. There were three different data types used in the experiment, SAR, AIS and VMS data. Two methods were used to compare the data, the automatic SUMO algorithm (see section 2.2) and manual observations. A total of 17 RADARSAT-1 and ENVISAT Alternating Polarization (AP) images were used to compare the different polarization and incidence angle combinations. On six occasions simultaneous recordings of SAR and AIS or VMS data from the group of shrimp fishing vessels in Hopendjupet were made.

The trial was a collaboration between the European Commission (EC) Joint Research Centre (JRC) and FFI, with support from the Norwegian Coast Guard, the Norwegian Directorate of Fisheries and Kongsberg Satellite Services AS (KSAT). VMS data from the Directorate of Fisheries and data from the Coast Guard's airplane were used. The Coast Guard flies over an area of interest, and use three methods to obtain information about fishing vessels in the area: (1) record AIS data sent from the fishing vessels, (2) use radar, and (3) do visual inspections.

Table 1 shows an overview of the SAR images obtained for the campaign. Some of the images were ordered by JRC and some by FFI.

Table 1. Information about the images acquired in Hopendjupet during the spring 2006.

| Image | Date | Time (UTC) | Asc/ Desc | Satellite | Swath | Pol | Ships in image (SUMO) | Fishing fleet in image | AIS | VMS |
|-------|------|------------|-----------|------------|-------|-------|-----------------------|------------------------|-----|-----|
| 1 | 6/4 | 14:53:04 | Asc | RADARSAT-1 | SNB | HH | 12 | + | + | - |
| 2 | 10/4 | 04:39:54 | Desc | RADARSAT-1 | SWA | HH | 6 | - | +* | + |
| 3 | 10/4 | 14:35:27 | Asc | RADARSAT-1 | SNB | HH | 2 | - | +* | +* |
| 4 | 10/4 | 14:36:10 | Asc | RADARSAT-1 | SNB | HH | 2 | - | +* | +* |
| 5 | 13/4 | 14:49:19 | Asc | RADARSAT-1 | W3 | HH | 15 | + | + | + |
| 6 | 20/4 | 14:44:58 | Asc | RADARSAT-1 | SNB | HH | 11 | + | + | + |
| 7 | 26/4 | 09:20:23 | Desc | ENVISAT | IS2 | HH/HV | 0 | - | - | +* |
| 8 | 26/4 | 09:20:38 | Desc | ENVISAT | IS2 | HH/HV | 0 | - | - | +* |
| 9 | 28/4 | 08:17:28 | Desc | ENVISAT | IS7 | HH/HV | 0 | - | - | + |
| 10 | 28/4 | 08:17:43 | Desc | ENVISAT | IS7 | HH/HV | 0 | - | - | + |
| 11 | 14/5 | 14:44:54 | Asc | RADARSAT-1 | SNB | HH | 1 | + | + | + |
| 12 | 26/5 | 08:37:36 | Desc | ENVISAT | IS6 | HH/HV | 0 | + | - | + |
| 13 | 26/5 | 08:37:51 | Desc | ENVISAT | IS6 | HH/HV | 3 | + | - | + |
| 14 | 27/5 | 09:46:19 | Desc | ENVISAT | IS1 | VV/VH | 0 | - | +* | - |
| 15 | 28/5 | 09:14:39 | Desc | ENVISAT | IS2 | HH/HV | 1 | - | - | + |
| 16 | 28/5 | 09:14:54 | Desc | ENVISAT | IS2 | HH/HV | 4 | - | - | + |
| 17 | 29/5 | 08:43:31 | Desc | ENVISAT | IS7 | HH/HV | 0 | - | +* | +* |

*: Data obtained are not inside the SAR image

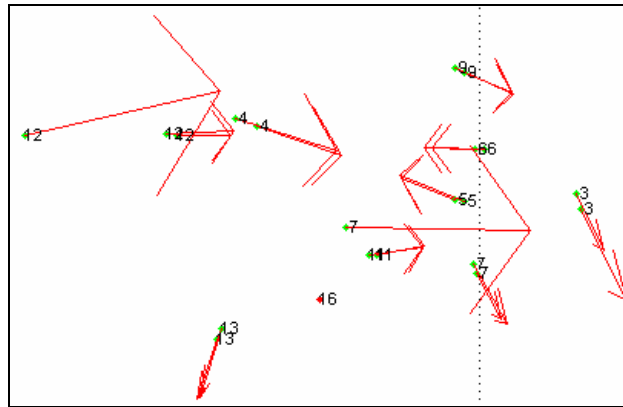


Figure 3. AIS data from the Norwegian Coast Guard propagated towards the time of the SAR image.

The AIS and VMS data were not always obtained at the time of the satellite pass. To compensate for this, course and speed from the AIS data from the Coast Guard were used to propagate the position backward or forward in time. Thus, a calculated position was obtained for the time the SAR image was taken. Up to three AIS messages from each ship were stored during a flyby, and the one closest in time to the SAR satellite pass was used in the calculations. Figure 3 shows an example of how the positions were propagated in time. All the arrows point to the propagated position at the time of SAR image, while the green dots are the positions obtained from the AIS data.

The VMS data were provided without vessel ID by the Directorate of Fisheries. The data included a vessel number, time and position (latitude and longitude). We have not tried to correlate the given vessel number with the correct vessel ID. If there were two VMS positions before and after the SAR image in time, the new position was calculated between the original positions. If only one VMS position was obtained, and the time of the VMS-position was far apart from the time of the SAR image, the data were not very useful.

2.2 SUMO ship detector

The SAR images were analysed with the SUMO ship detection software. SUMO is a Constant False Alarm Rate (CFAR) detector developed at JRC [4]. Its principle of operation is as follows. As a first step, it applies a land mask, after obtaining image geo-positioning from the image file header. Secondly, it divides the image in rectangular tiles and calculates the mean and standard deviation in each tile. In this calculation, high pixel values are not used, avoiding contamination of the sea clutter statistics by bright target pixels. The mean and standard deviation obtained are used together with the Equivalent Number of Looks (ENL) of the SAR image product as the three parameters that define a K-distribution. On the basis of this distribution a threshold is defined (still for each tile separately) for a chosen false alarm rate (typically 10^{-7}). Pixel values over the threshold are registered as detections, and neighbouring detected pixels are clustered into targets (also crossing tile boundaries). This process finds ships, but also some bright sea surface features. The latter are often characterised by a more extended area with high pixel values, and such occurrences are flagged as unreliable. A rectangle is fit to each target cluster, from which length, width and heading of the target are derived. The procedure is fully automatic and results in a file with a list of targets found in the image, each with location (pixel row, number, as well as latitude and longitude), length, width, heading, significance and reliability. Significance is defined as the peak pixel value in terms of standard deviations over the mean of the clutter background. Experience shows that detections with the lowest significance need to be discarded because they are likely to be false alarms, although formally above the CFAR threshold. (This means that the actual distribution function of the sea clutter pixel values is not precisely modelled by a K-distribution, but has a longer tail.) Reliability is assigned in four classes, based on the shape of the target cluster and the number of high pixel values in the immediate surroundings: high confidence (sure ship), low confidence (probable ship), very low confidence (probable noise) and zero confidence (most likely noise). The latter is usually immediately discarded. In addition, an overview image is produced including the detected target locations indicated.

The above functionality is implemented in Java and runs on a normal PC analyzing a 100 x 100 km SAR image (of 8,000 x 8,000 pixels) in one minute. Although fully automatic, it is possible to improve the results by subsequent visual inspection of the detections. A human analyst is able to recognise some false alarms based on the detailed shape of the target. Similarly, an analyst can recognise the presence of a weak target, below the

detection threshold, if he is pointed to its location on the basis of other information (such as AIS or VMS records). SUMO provides a user interface to visually inspect the SAR image and overlay VMS and AIS positions. So by visual inspection, the results of an automatic SUMO run can be somewhat improved, although in that case it takes longer than one minute. This has been done for the present study.

2.3 Analyses

2.3.1 April 6th at 14:53:04 (UTC)

The RADARSAT-1 image is ScanSAR Narrow B. The SAR image covers Hopen djupet, which is located around 75°N, 30°E. Using SUMO, 10 fishing vessels are detected in a group near 75.2°N, 35.5°E, where nine of them are detected with high confidence and one is detected with low confidence. Using manual observations, all ten vessels are detected with traditional image interpretations. The Coast Guard could detect and identify all of them using AIS and manual observations (Figure 4). A 52 m long fishing vessel (top) was not reporting through AIS, but was detected both by SAR and by the Coast Guard's manual observations (red dot in Figure 5). The vessels detected have lengths between 51 m and 70 m. Two other vessels are detected in the SAR image far away from the group of fishing vessels, but these are not confirmed by AIS or manual inspections. VMS data were not available.

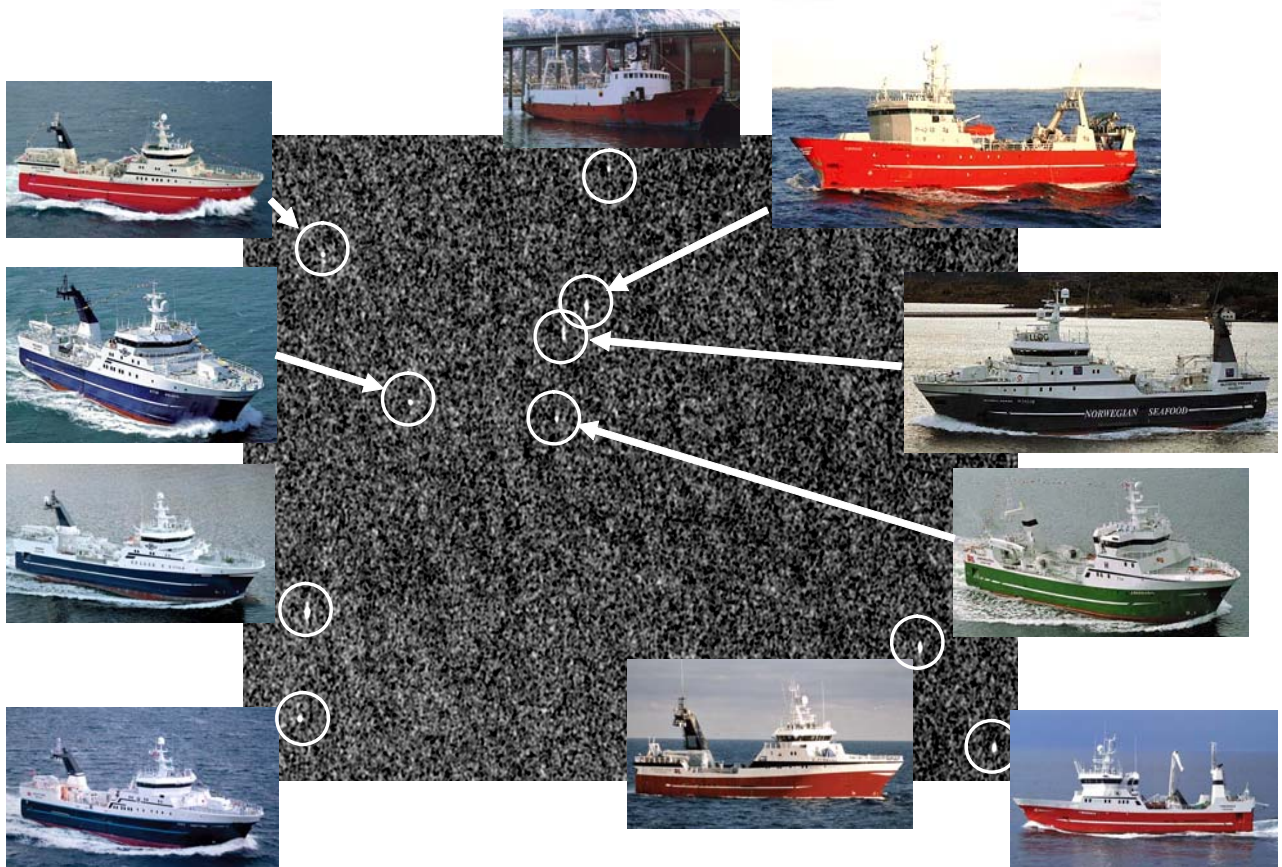


Figure 4. Ten vessels fishing for shrimps detected in the SAR image and identified using AIS data and manual observations from the Coast Guard. ©ship-info.com for vessel images. ©FFI/KSAT for SAR image.

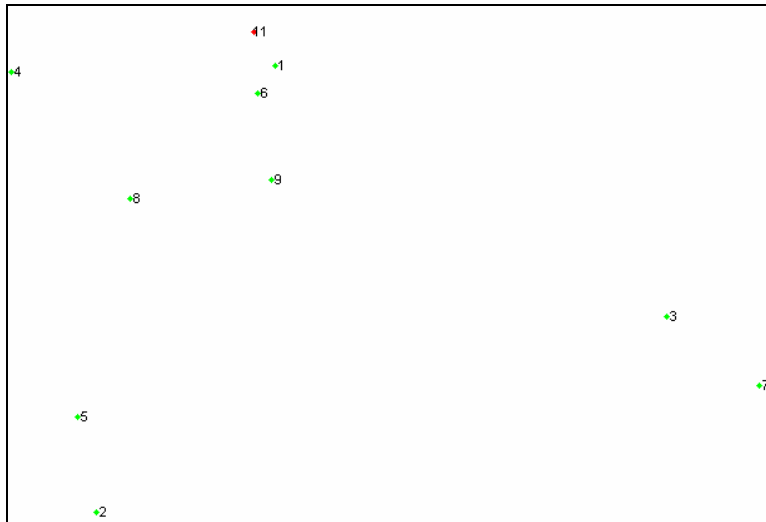


Figure 5. Example of plot including AIS data from the Coast Guard. The positions reported through AIS coincide with those in the SAR image.

2.3.2 April 10th at 04:39:54

The RADARSAT-1 image is ScanSAR Wide A. This image mode covers 500 x 500 km. Its resolution of 100 m is quite low considering the target sizes, and in its near range the incidence angle goes down to 20° which is known to be unfavourable for ship detection. The shrimp fishing fleet is just north of the SAR image, so the AIS positions and manual observations from the Coast Guard cannot be used for this image. Five vessels are detected by SUMO with high confidence with manual corrections in the far range of the image. All these vessels were also reported by VMS. For three of them, approximate VMS positions are shown in white circles in the cut of the SAR image (Figure 6). The yellow circle shows the vessel detection where the VMS position is a little bit northeast. One vessel on the edge furthest north in the image detected with low incidence using SUMO does not have a VMS position. There are an additional three VMS-reported vessels inside the SAR image which are not detected in the SAR image. The vessels' sizes are not known.

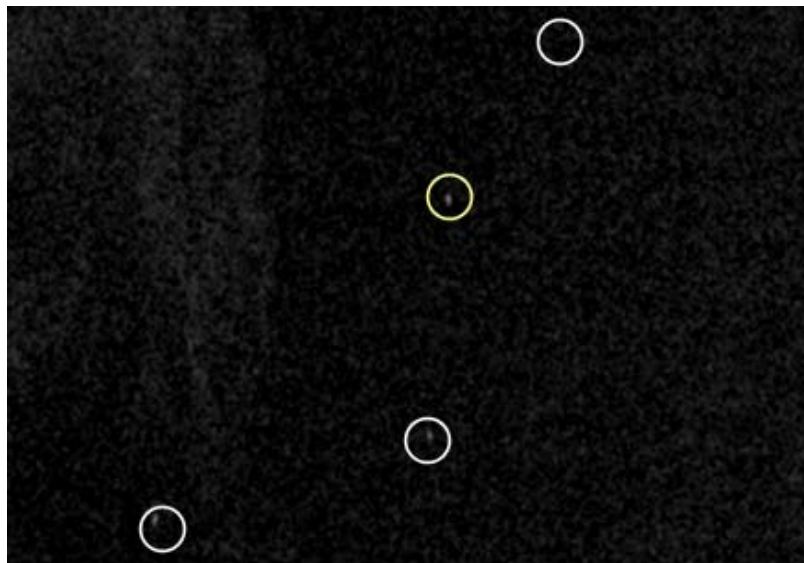


Figure 6. VMS positions are shown in white circles. The yellow circle shows the vessel detection where the VMS position is northeast.

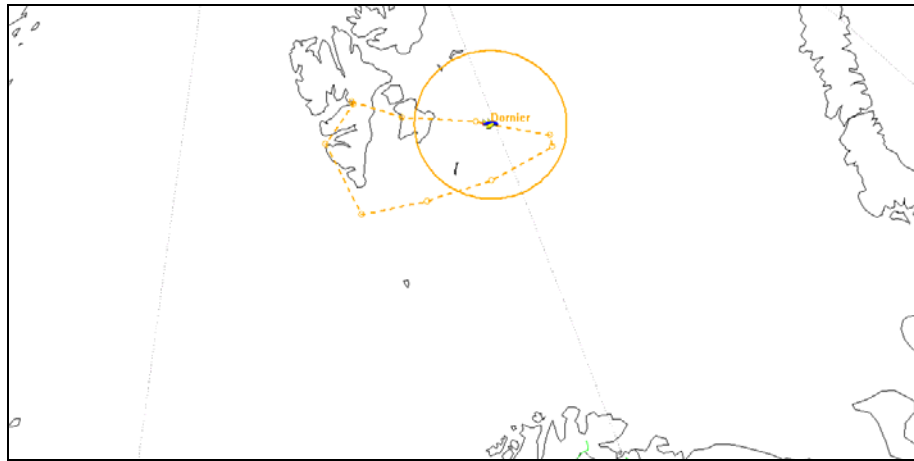


Figure 7. Flight track for the Coast Guard on April 10th.

2.3.3 April 10th at 14:35:27 and 14:36:10

There are two adjacent RADARSAT-1 ScanSAR Narrow B images on April 10th. Unfortunately, the shrimp fishing fleet is again just north of the SAR images. Thus, the AIS positions and manual observations from the Coast Guard cannot be used. Using SUMO, one vessel is detected with high confidence and three vessels are detected with low confidence. None of the reported VMS positions were inside the SAR image, so the SAR detections cannot be verified. Figure 7 shows the Coast Guard's flight track for April 10th. The circle indicates the local horizon seen from the aircraft. AIS data is received from vessels within this footprint.

2.3.4 April 13th at 14:49:19

The RADARSAT-1 image is Wide 3, and it covers the fishing fleet. The SUMO algorithm detected 13 vessels with high confidence in the SAR image, while 2 vessels are detected with low confidence north-west of the group of fishing vessels. The 13 vessels inside the group of fishing vessels are also detected manually. Twelve of the 13 vessels have transmitted AIS information or are detected by the Coast Guard's airplane. The left part of Figure 8 shows a cut of the SAR image with the SUMO detections. The right part of Figure 8 shows the AIS positions and the Coast Guards manual observations. Two of the vessels were reporting through the AIS system, and were also observed manually by the Coast Guard. By comparing the two figures, one can see that there is one extra detection in the SAR image compared to what the Coast Guard has observed. One reason may be because the Coast Guard started reporting around 20 minutes after the SAR image was recorded. Thus, the ship may have moved outside the group of fishing vessels. Another reason for the difference might be that the detection is noise instead of a vessel; the SAR target in the bottom left of the white circle in Figure 8 is the weakest of all targets, although still at 12 standard deviations over the mean of the background clutter. The detected vessels range between 50 m and 71 m.

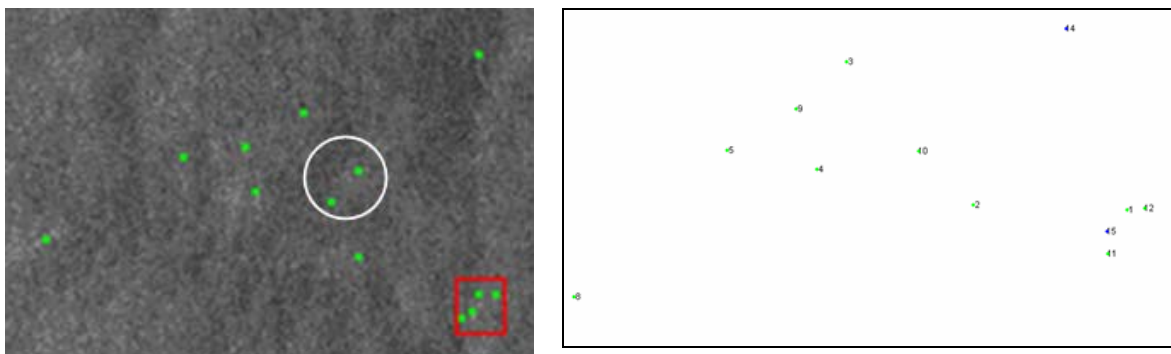


Figure 8. Left: Vessel detections in the SAR image using the SUMO algorithm. Right: Vessel positions using AIS data and manual observations obtained by the Coast Guard. The data coincide well in the left and the right images.

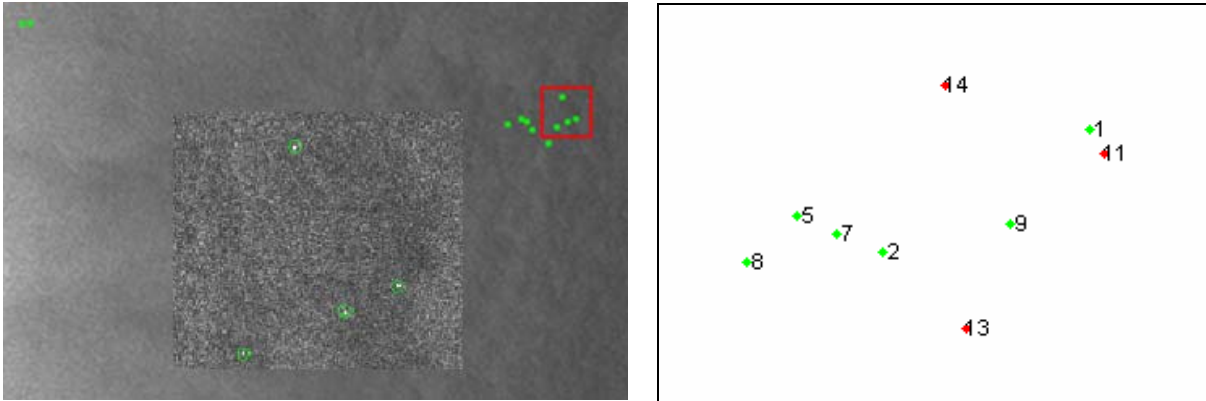


Figure 9. Left: Eleven vessels are detected in the SAR image on April 20th. The middle of the image shows the red area enlarged. Right: AIS data and manual observations from the Coast Guard. Vessel number 11, 13 and 14 have not reported through AIS.

2.3.5 April 20th at 14:44:58

The RADARSAT-1 image is ScanSAR Narrow B, and it covers the fishing fleet. The SUMO vessel detector was used with a slightly lower threshold than usual, but without manual corrections. 11 vessels are detected in the SAR image using SUMO and manual detection (Figure 9). Nine vessels of the shrimp fishing fleet are detected in a group. This is according to the AIS data and manual observations obtained from the Coast Guard. There are two vessels detected to the left in the SAR image, while there are three reported AIS targets in that area. The reason why only two vessels are detected in the SAR image might be because two of the vessels are close together, so they appear as one bright spot in the SAR image. Three vessels did not report through AIS inside the group of fishing vessels and two did not report outside the group of fishing vessels, but all were detected manually by the Coast Guard. Compared to the plot using Coast Guard data, two targets were missed in the SAR image, Coast Guard plot target number 4, which is in the very near range, and a target north-east of the group of shrimp fishing vessels. The detected vessels' lengths are between 50 m and 67 m.

2.3.6 April 26th and 28th

Two ENVISAT images were obtained on each day of April 26th and April 27th using Advanced Synthetic Aperture Radar (ASAR) AP mode, and sub swath IS2 on the 26th and IS7 on the 28th. No ships were detected in the images using SUMO and manual detections. This conforms to the Coast Guard's report sighting the vessels around 76°N, 30°E, which is outside of the imaged areas.

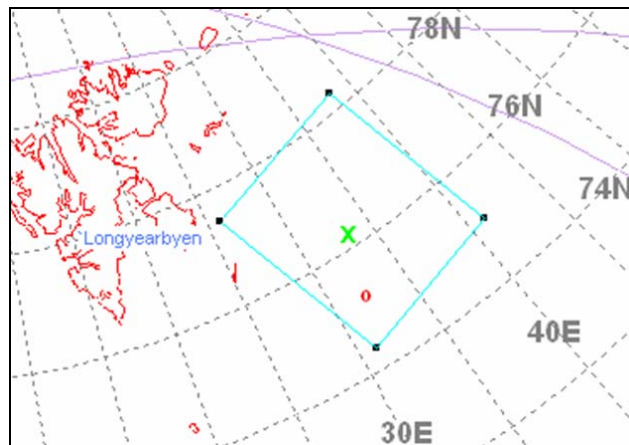


Figure 10. Coverage of SAR image and location of fishing fleet on May 14th.

2.3.7 May 14th at 14:44:54

The RADARSAT-1 image is ScanSAR Narrow B. The SAR image from May 14th covers the reported fishing fleet. Figure 10 shows the coverage of the SAR image (turquoise square), the last reported location of the fishing fleet (May 11th at 76.2°N and 33°E, green cross), and the only ship detected in the SAR image using SUMO and manual detection (red circle). This target could not be verified by AIS or VMS. A number of false detections made by SUMO on the ice edge in the top left of the SAR image was removed by hand.

2.3.8 May 26th at 08:37:36 and 08:37:51

The two ENVISAT AP mode images were ordered using sub swath IS6. Three vessels are detected with high confidence in both polarizations (HH and HV) at 08:37:51 UTC using SUMO and manual detections (Table 2). Five VMS targets are reported inside the SAR image. Table 3 shows information about the positions of the VMS targets. The time means how far from the time of the SAR image the VMS information was obtained. VMS target number 1 is close to the target north-east in the SAR image. VMS target number 5 is closest to the SAR target most south-west in the SAR image, but there is an uncertainty in time. A position at the time of the SAR image is calculated using the two VMS positions that are closest in time, 02:58 and 04:58 UTC. VMS targets 2, 3 and 4 are outside the SAR image.

2.3.9 May 27th at 09:46:19

One ENVISAT AP mode image was ordered using sub swath IS1. No vessels are inside the ENVISAT ASAR image according to the Coast Guard's reports. No vessels are detected using either SUMO or manual detections. There are no VMS data obtained this day.

2.3.10 May 28th at 09:14:39 and 09:14:54

Two ENVISAT AP mode images were ordered using sub swath IS2. In the image furthest north, obtained 09:14:39, one vessel was detected in the HH-channel with high confidence using SUMO. The vessel was neither detected automatically or manually in the HV-channel. In the SAR image at 09:14:54 four vessels were detected with low confidence using SUMO. Also these targets were only detected in the HH-channel. All reported VMS targets are outside the ASAR images. There were no AIS data obtained this day. Thus, it is not possible to check if these targets are really vessels. It is possible that they are false alarms as all of them are only at the 9-10 sigma level.

2.3.10 May 29th at 08:43:31

One ENVISAT AP mode image was ordered using sub swath IS7. No ships were detected in the SAR image. There were no reported VMS or AIS targets inside the SAR-image.

Table 2. Information about the detected vessels in the SAR image.

| SAR | Lat (°N) | Long (°E) | Location | TCR | Inc. angle (°) |
|-----|----------|-----------|------------|---------------------|----------------|
| 1 | 76,1008 | 34,2420 | North-east | HH: 12.25 HV: 11.66 | 39.28 |
| 2 | 75,8635 | 32,6050 | Middle | HH: 11.77 HV: 2.86 | 41.15 |
| 3 | 75,8427 | 32,0690 | South-west | HH: 14.28 HV: 8.92 | 41.83 |

Table 3. Information about the position of the VMS targets.

| VMS | Lat | Long | Time (min) |
|-----|------------|------------|------------|
| 1 | 76,1008333 | 34,2427778 | 0 |
| 2 | 74,1068796 | 33,9513889 | 2 |
| 3 | 74,0694444 | 33,6591667 | 25 |
| 4 | 74,1058241 | 33,9014815 | -2 |
| 5 | 75,829892 | 31,9899151 | -340 |

3 DISCUSSION

Any knowledge about polarization combinations gained by the trial could be valuable as a preparation for the European Sentinel-1 satellite, which will continue earth observations after ENVISAT. The planned launch date for Sentinel-1 is 2011, and the planned polarization combination on Sentinel-1 is VV/VH. VV is not good for ship detection due to high reflection from the sea, but the low reflection from the sea using cross-polarization makes VH and low incidence angle a new alternative for ship detection. HH-polarization is used before in combination with high incidence angles for vessel detection. The discussion of polarization and incidence angle combination is quite difficult using the results from this campaign since in the end there were few ENVISAT images that covered known vessels.

Some problems with the satellite orders were noticed. ENVISAT, when ordered two weeks in advance, has an attractive price. However, this advance period is really too long for the present purpose of monitoring a mobile fishing fleet. When ordering on shorter notice, the price advantage disappears, and even with a few days advance notice there is still a considerable risk of missing the fleet. In addition, there were some cancellations and conflicting orders, as a result of other users acquiring imagery nearby in other modes. RADARSAT-2 will have polarimetric capability, a maximum ordering time of 3 days and in addition good coverage (300 km x 300 km), which results in a better chance to capture a mobile fleet.

4 CONCLUSIONS

The Høpendjupet trial has shown the benefit of using SAR, AIS and VMS together for ship detection and tracking. AIS and visual data were obtained from the Norwegian Coast Guard's aircraft. VMS data were obtained from the Directorate of Fisheries. Seventeen SAR images were obtained, where 7 were RADARSAT-1 images and 10 were ENVISAT images. The shrimp fishing fleet was inside six of the SAR images. AIS and VMS data were obtained at the same time for three of the six images including the fishing fleet. For the last three images, AIS data were obtained for one and VMS data were obtained for two images.

Radar satellites can detect ships not reported by AIS and VMS, while the ships detected with SAR can be identified using AIS and VMS. For the tracking services, the correlation of the two sources gives the opportunity to unveil vessels neglecting transmission of mandatory vessel and voyage reports. The trial has been useful to validate SAR, AIS and VMS, and to look at ways to improve the Coast Guard's operative capability.

The trial was also done to further develop vessel tracking services and ship detection algorithms for SAR. Future work should be to develop further services based on satellite radar images, and to exploit new modes and satellites that will be launched in the future.

To be able to have an operational service in Norway, it is necessary that (a) the time between the order of the SAR image and its acquisition is short and (b) the time between SAR image acquisition and completed analysis is near real time. At the moment, (b) has been achieved but (a) not.

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