Collaborative use of SAR and AIS data from NovaSAR-S for Maritime Surveillance
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Abstract
This paper provides a novel approach for the fusion of Synthetic Aperture Radar (SAR) images and Automatic Identification System (AIS) data for the tracking of vessels over sea areas. At this aim, SAR and AIS data are simulated and optimized for the upcoming NovaSAR-S maritime and stripmap modes. These simulated data are used to test the proposed tracking methodology in real time scenario. The results also give practical guidelines on how to task NovaSAR-S to cover uncooperative vessels over the revisit time of the satellite considering the Doppler shift due to the radial velocity of the target.

1 Introduction
In the last years, maritime surveillance domain has seen a significant increase in the development of new methods and algorithms to deliver an efficient ship monitoring system that could provide more security at sea in areas dealing with illegal activities including illegal fishing, piracy and smuggling [1-3].

This can be done by exploring all possible sources of information available: SAR sensors which can provide high resolution images independently of day light and weather conditions [4]; Vessel Monitoring System (VMS) which was initially developed to provide fisheries data on location, course and speed of ships; the Long-Range Identification and Tracking (LRIT) system which provides a global view for ship tracking and identification; and, finally, the Automatic Identification System (AIS) which broadcasts real time information of ships including name, dimension, position and heading [5]. These systems are introduced to enhance maritime traffic security at sea. This paper will look at a new methodology to combine SAR and AIS data for ship tracking that can be easily implemented for operational environments.

As specified by the International Maritime Organization (IMO), the AIS is a Very High Frequency (VHF) transponder which is a mandatory carriage system on board of vessels that broadcast real time information in underway or at anchor status [5]. The AIS was initially used for ship collision avoidance: ship communicates its information to other ships and to offshore stations. The temporal interval in which ships update their navigation information depends on the type of information itself. The dynamic information, including position, speed and heading, is updated every 2 to 10 seconds and every 3 minutes while at anchor status. Static information, including the Vessel ID, type, size and call sign, is updated every 6 minutes. The drawback of the AIS is the coverage limitation. The terrestrial AIS stations, indeed, may not be able to receive AIS signals from ships farther than 40 km offshore due to the curvature of the Earth. However, in 2004, the Norwegian Defence Research Establishment (FFI) has proven that the AIS signal can be captured from space in low Earth orbit (LEO) with very high detection probability from around 1000 ships. Indeed, the coverage in this case is much larger and is limited by the footprint of the satellite [6]. For example, at an altitude of 650 km in low Earth orbit and an angle 78° between the nadir and the lowest elevation angle, the satellite can cover more than 20 million km² within the assumption that the footprint has a circular shape. Consequently, the development of spaceborne AIS platforms has become of worldwide interest. For example, the upcoming NovaSAR-S satellite, a low-cost satellite working in S band, can provide both SAR and AIS data from the same platform [7].

The most common ship detector for maritime surveillance in SAR imagery is the Constant False Alarm Rate algorithm (CFAR). In this detector, the sea clutter is modelled by a statistical distribution and a threshold is computed according to a fixed probability of false alarm [1]. The pixel or group of pixels under test are considered as a target if their intensity is above this threshold. This is sometimes followed by the validation step using AIS data. However, the AIS can be simply turned off by non-cooperative ships for illegal activities as happened for the hijacking of the supertanker MV Sirius Star in Somalia (Africa) [8]. For this reason, it is important to understand how SAR and AIS data can complement each other and what happens if one system (in this case the AIS) is no more available. This problem has been addressed using a
variety of techniques. For example, Mazzarella et al. [9] proposed the fusion of the ship detection result from SAR images with historical AIS data. Historical AIS data are collected from collaborative ships, used to create a traffic pattern map, then linearly propagated to the SAR acquisition time. The detection results from SAR are projected into this map and the results are evaluated by a weighted distance. However, this method may not be applied in the case where the ship is hijacked, lost or its AIS has been turned off. In this paper a new methodology is proposed to derive future positions of a non-collaborative ship from the fusion of SAR and AIS data available for that ship till the time its AIS signal disappears. The introduction of the relevant theoretical framework and the corresponding constraints will be essential and of practical use to understand how to tactically task any joint SAR&AIS mission, like the NovaSAR-S one, in emergency maritime situations.

The paper is organised as follows. Section II outlines the main methodology including data simulation and a detailed block diagram summarizing the different steps of processing and tasking through which the methodology of combining SAR and AIS data is implemented. This is followed by preliminary results and a short discussion in Section III. The conclusions and future perspectives are finally discussed in Section IV.

2 Ship tracking methodology

In this section, we firstly explain the different steps adopted to simulate SAR data and then introduce the block diagram for the ship tracking. For sake of simplicity, only, NovaSAR-S will be considered as a case study, but the procedure is general and can be applied to any SAR/AIS mission or, potentially, to two distinctive SAR and AIS missions.

2.1 NovaSAR-S and SAR simulation data

NovaSAR-S is a spaceborne SAR programme resulted from the collaboration of Surrey Satellite Technology Ltd (SSTL) and Airbus Defence and Space (Airbus DC) with the support of UK government [7]. NovaSAR-S is the first low cost S-band (3.1-3.3 GHz) SAR system with capability of providing high resolution SAR images up to 6 metres in stripmap mode with polarisation up to quad polar operations [10]. In addition, the AIS receiver is the second payload onboard of NovaSAR-S platform [7]. Thus, NovaSAR will be an interesting source of data where the SAR and the AIS data can be potentially delivered from the same platform on the same area at approximately the same time. Table I provides more details about NovaSAR-S features in different acquisition modes.

The SAR images are simulated in two steps using Monte-Carlo approach. Firstly, the exponential distribution is assumed for the sea clutter intensity. Its mean value is set equal to that corresponding to the single scattering from rough sea within Geometric Optics (GO) approximation which takes the radar parameters (frequency, look angle and spatial resolution), roughness parameters and the dielectric of the saline water as an input [11]. The ship backscatter is simulated using the canonical model presented in [12]. In addition, the AIS data is simulated by adopting the static information from maritime traffic website [13]. The initial dynamic information including the position, speed and heading is given randomly. Figure 1 illustrates an example of a simulated SAR intensity image for the stripmap mode of NovaSAR-S for a sea surface with a single ship backscatter.

2.2 Ship monitoring procedure

The flowchart in the Figures 2 illustrates in detail the process of maritime monitoring of an uncooperative ship. To simulate this scenario, for some given static information of a ship (length, width and unique identifier number) retrieved from the AIS provider, its initial dynamic AIS data (position, speed and heading) is randomly associated. Once the stripmap image is simulated, the CFAR algorithm is applied to generate a map of detected ships. The uncooperative ship is assumed to be in the coordinates (x0, y0) (Ground range, Azimuth). The heading and the speed are taken from the AIS data. We assume that in practice a non-cooperative ship would sail at its max speed $V_{max}$ trying to escape any

![Figure 1: Simulated SAR stripmap intensity image of the sea clutter with the presence of a single ship.](image)
possible tracking, satellite and non, by leaving the area from which the last AIS signal was received. We also assumed that it would keep the same heading $\theta$ (the angle between the range direction and the ship trajectory as depicted in Figure 3) to avoid additional manoeuvres. For the sake of simplicity, the SAR and AIS data are assumed to be acquired at the same time. Thus, see Figure 3, the estimated position of the ship $(x_{\text{max}}, y_{\text{max}})$ after a period $T$ (the minimum time before a SAR dataset, from the same platform or another, becomes available) is given by equation (1):

$$\begin{align*}
x_{\text{max}} &= D_{\text{max}} \cos \theta + x_0 \\
y_{\text{max}} &= D_{\text{max}} \sin \theta + y_0
\end{align*}$$

(1)

where $D_{\text{max}}$ is the maximum distance travelled by the ship under maximum speed $V_{\text{max}}$ and $\theta$ the heading of the ship during the period $T$.

The authors propose that, in this scenario, the satellite is tasked in a way that maximise the likelihood to have the uncooperative ship imaged. This automatically means acquiring a SAR image with the widest possible coverage and swath (for NovaSAR-S this would mean an acquisition in the maritime mode). At this purpose, a positive empirical increment $\delta$ is considered in the definition of the new image centre coordinates given by equation (2):

$$\begin{align*}
x_c &= x_{\text{max}} - S_1 (1/2 - \delta) \text{sign}(x_{\text{max}}) \\
y_c &= y_{\text{max}} - W_1 (1/2 - \delta) \text{sign}(y_{\text{max}})
\end{align*}$$

(2)

where $S_i$ and $W_i$ are respectively the swath and the width of the SAR image and the function $\text{sign}(.)$ returns the sign of the estimated coordinates. The quantity $\delta W_1$ should at least equal to the azimuth offset of a moving ship (not still) to ensure that the ship can be imaged in the second SAR acquisition. This azimuth shift $\Delta y$, provided in [14], is here reported in equation (3) for sake of completeness.

$$\Delta y = \frac{R V_{\text{max}} \cos \theta}{V_s}$$

(3)

where $V_s$ is the satellite velocity and $R$ is the slant range of the relative target.

The proposed configuration of the centre would potentially maximise the monitored area which would

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**Figure 2:** Ship monitoring flowchart with NovaSAR-S.

**Figure 3:** The tasking strategy to define the centre the second SAR image with larger coverage possible.
result into better chances of detection of uncooperative ships. Once the second image is acquired and centred in \((x_c, y_c)\) as shown in Figure 3, the CFAR algorithm is applied to the new SAR image. If we assume that all other ships in the image are cooperative and broadcast their AIS data, these will be clearly identified by the AIS data and masked out from the SAR image. Therefore, only ships that do not communicate their AIS signal or ship-like objects remain in the image. To strengthen the identification, the ship dimension error is performed against the saved ones at the beginning of the chain using equation (4).

\[
\begin{align*}
\varepsilon_l &= |l_i - l_0| \\
\varepsilon_w &= |w_i - w_0| \\
\varepsilon &= \varepsilon_w + \varepsilon_l
\end{align*}
\]  

(4)

where \(l_0, w_0\) are the length and width of the ship in the first SAR image, \(l_i, w_i\) are the length and width of the ship detected in the second SAR image acquired after a time \(T\) and \(\varepsilon_l, \varepsilon_w, \varepsilon\) are, respectively, the error in the length direction, in the width direction and the total error. The uncooperative ship is identified as the target presenting a total error smaller than the sum of the resolutions \(\Delta x, \Delta y\) in range and azimuth direction respectively. Finally, the last product in Figure 2 is the map of the uncooperative ship detected and identified after a period \(T\).

3 Experimental results

To test the proposed system, a stripmap image is simulated in the S-band range of frequency and in an open sea scenario. The size of the image is 2200×3300 pixels in azimuth and range respectively with a resolution of 6 metres in both azimuth and range directions. Consequently, the image coverage is 13.2 km by 19.8 km. We considered a voyager ship as an example for the study.

![Figure 4: Intensity stripmap image of the sea clutter and a ship heading of 2°. The ship is considered out of the image after \(T\) time, the blue line represents the route of the ship.](image)

The blue line in the image in Figure 4 represents the first part of the arrow connecting the initial position (769, 1521) to the estimated position (90048, 4638) which is already out of the first image. Clearly, the ship is out of the coverage of the first image, thus, it is necessary to task the satellite to acquire a maritime mode SAR image over another location. The maritime mode SAR image is simulated in the S band. The issue of ambiguities arising from the undersampling of the maritime mode images [15] is here disregarded. The size of the maritime mode image is 29000×20300 pixels in azimuth and range respectively with square resolution of 13.7 metres for simplification. Thus, the image coverage is 278 km by 397.5 km. The maritime mode SAR image is centred in the coordinate given by the equation (2) with the empirical increment \(\delta\) set equal to 0.1. In this case, \(\delta W_1\) (27.8 km) is bigger than the azimuth displacement due to the radial velocity which is 0.93 km (≈ 68 pixels) according to equation (3). Consequently, the ship can be captured in the new acquisition although an azimuth shift \(\Delta y\) is present as shown in Figure 5. Therefore, using equation (2), the centre of the maritime mode SAR image is recommended to be in (78443, -3483). Then, based on the assumption made, the ship would be detected in the estimated coordinate plus an extra displacement in the
Azimuth direction in the maritime mode SAR image as indicated by the blue arrow in Figure 5. Then, as final step from Figure 2, a map of the identification and detection of the uncooperative ship will be generated.

The Doppler shift due to the radial velocity of the ship cruising with a speed of 20.1 knot is evaluated for all the 360 directions with a step of 1°. The highest displacement occurs for $\theta = 0°$ and is in the order of 68 pixels at resolution of 13.7 m. Finally, the normalised effective is evaluated: it is the intersection between the second SAR image and circle defined by the centre $(x_0, y_0)$ and the radius $D_{\text{max}}$ normalised by the area of the second SAR acquisition. Outcomes are shown in Table 2 and it results that the normalised effective area is at least equal to 76.20% (for $\theta = 90°$) with a maximum value of 98.49% for $(\theta = 307°)$.

Table 2: Doppler Shift and normalised effective area evaluation for all possible direction $\theta \in [0°, 360°]$.

<table>
<thead>
<tr>
<th>Satellite Parameters</th>
<th>Imaging frequency band</th>
<th>S-Band (3.1-3.3 GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Polarization</td>
<td>HH, HV, VH, VV</td>
</tr>
<tr>
<td></td>
<td>Mass</td>
<td>430 kg</td>
</tr>
<tr>
<td></td>
<td>Optimum Orbit</td>
<td>580 km</td>
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<table>
<thead>
<tr>
<th>Ship Information</th>
<th>Length</th>
<th>Width</th>
<th>Average Speed</th>
<th>Max Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>199.1 m</td>
<td>25 m</td>
<td>18.4 knot</td>
<td>20.1 knot</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Doppler dispalcet</th>
<th>Max displacement for $\theta = 0°$</th>
<th>Min for $\theta = 90°$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\theta \in [0°, 360°]$</td>
<td>$\theta = 90°$</td>
</tr>
<tr>
<td></td>
<td>930.9 m or 68 pixels</td>
<td>93.93 %</td>
</tr>
<tr>
<td></td>
<td>93.93 %</td>
<td>98.49 %</td>
</tr>
<tr>
<td></td>
<td>93.93 %</td>
<td>76.20 %</td>
</tr>
</tbody>
</table>

4 Conclusions

This paper provides general theoretic considerations, an example and practical guidelines for the tracking of non-cooperative ships from the moment in which AIS data are no more transmitted from the ship and SAR data are the only source of information on which any forecasting on future ship positions can be based. Worst case scenarios have been simulated by considering SAR and AIS interoperability till the moment the ship starts not cooperating. First simulations show that, by properly modeling the actual emergency scenario, the two different datasets can indeed “feed” each other and allow at least the optimization of the following SAR tasking when the AIS of some ships are off. The results from the practical example, based on the NovaSAR mission parameters, show that the ship can be tracked after 14 hours using maritime mode SAR image from NovaSAR-S constellation of 3 satellites. The second SAR image is acquired considering the azimuth Doppler displacement due to the radial velocity of the target in which the non-co-operative ship is always imaged considering the maximum ship speed provided by the AIS data. Finally, the effective area is evaluated for all heading directions resulting in an average value of 93.93%.

References


