Remote Sensing for Maritime Monitoring and Vessel Prompt Identification

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Abstract. The main purpose of the work described in this paper concerns the development of a platform dedicated to sea surveillance, capable of detecting and identifying illegal maritime traffic. This platform results from the cascade implementation of several image processing algorithms that take as input Radar or Optical maps captured by satellite-borne sensors. More in detail, the processing chain is dedicated to i) the detection of vessel targets in the input map, ii) the refined estimation of the vessel most descriptive geometrical features and, finally, iii) the estimation of the kinematic status of the vessel. This platform will represent a new tool for combating unauthorized fishing, irregular migration and related smuggling activities.

Keywords: Maritime traffic monitoring, SAR sensing, Optical sensing, Ship detection, Image segmentation, Image classification, Wake detection and analysis

1 Introduction

Maritime traffic consists of more than 600.000 vessels navigating daily all over the world seas. This huge network of vehicles poses hard issues for what concerns monitoring purposes and timely countermeasures implementation. Satellite missions rotating along earth-centered orbits provide heterogeneous remote sensing data about the sea surface status on a daily basis and at different resolutions. Remote sensing data play a crucial role for vessel monitoring purposes, providing information about the vessel main features, its peculiar geometry and its kinematics.

The main goal addressed in this paper concerns the development of a software platform dedicated to sea surveillance, capable of detecting and identifying seagoing vessels. This platform will be in charge of collecting and integrating data made available by multi-source, multi-sensor satellite missions for specific maritime areas. High-resolution data will be provided by currently orbiting satellites such as European Space Agency (ESA) Copernicus Sentinels, ISI-IMAGESAT

EROS and Italian Space Agency (ASI) COSMO-SkyMed. The data will then be processed in order to detect and identify the ships located in the area of interest and to provide estimates of meaningful ship features, such as shape and kinematics parameters.

The proposed maritime monitoring platform has been conceived as a sequential chain of procedures (figure 1), each addressing a specific task oriented to the extraction of meaningful information.

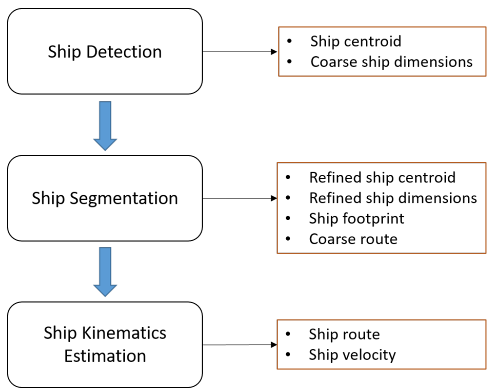

Fig. 1. Block diagram for the proposed maritime surveillance platform.

First, radar and optical images, represented in the Universal Transverse Mercator (UTM) coordinate system, are processed by a dedicated detection algorithm, inspired to state-of-the-art literature [1], that identifies potential vessels by discerning between sea background and backscattering anomalies. The output of this procedure is a set of submaps cropped from the input image so that a single target per crop is observed. These crops are then fed to a ship segmentation module [2] in charge of refining the identification of those map pixels that belong to the target. Accordingly, this operation provides additional information on the target, such as the length overall, the beam overall and the heading orientation (estimated with a 180° ambiguity, unless the velocity vector is estimated or the bow is distinguishable in the image). The morphological information provided by the latter module can be further enriched by inspecting the water surface surrounding the detected ship. Indeed, it is known that the ship's passage through the water generates a specific wake pattern whose features depend directly on the ship's kinematics ([3,4]). In particular, by detecting the linear envelopes of the main wake components and performing a frequency analysis of the observable wake oscillations, it is possible to estimate, respectively, the ship's heading (univocally) and the ship's velocity.

The rest of the paper is arranged as follows: section 2 concerns a detailed discussion of the adopted processing techniques. Section 3 presents an actual implementation of the discussed platform within the framework of OSIRIS, a project funded by ESA. Section 4 concludes the paper by presenting a summary of the main results and discussing future developments.

2 Processing techniques

A main goal within the mentioned platform is to develop computational imaging procedures to process Synthetic Aperture Radar and Optical data returned by satellite sensors. We propose a system for the automatic detection and recognition of all the vessels included in a given area of interest. The maritime satellite imagery will be processed to extract visual informative features of candidate vessels and to assign an identification label to each vessel. The remaining parts of this section concern detailed descriptions of each processing stage that contribute to the fulfillment of the aforementioned tasks.

2.1 Ship detection

The detection algorithm aims at identifying those regions in the input image data that most likely include vessels. The output of a positive detection is a subset (crop) of the input image, restricted to an Area of Interest (AoI) where only the candidate vessel is visible.

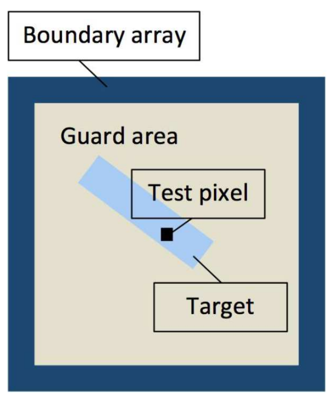

Fig. 2. CFAR detector moving window.

In case of SAR imagery, the choice of the most suitable detection method strongly depends on image features such as spatial and radiometric resolution, number of looks, transmitted and received polarization, and the like. As speed is a major requirement for prescreening, fine statistical considerations are normally overlooked to obtain fully automatic and fast detectors based on simplified statistical assumptions and a fixed maximum false-alarm rate. This is the principle of the different types of Constant False-Alarm Rate (CFAR) detectors. They normally work on single-channel intensity images, and consist in statistical tests over each pixel intensity against the intensities of a specified neighborhood. In practice, ([1,5]) a moving window centered on the test pixel scans the entire image. This window (figure 2) is formed by a test pixel neighborhood (*guard area*), which is supposed to contain any possible target that includes the test pixel, and a second neighborhood (*boundary array*), only supposed to contain background pixels, which is used to estimate the background statistics. CFAR is a type of adaptive threshold method: once the required false-alarm rate is fixed, the background probability density function $f(x)$ (usually a Gaussian), where x is the pixel value, is assumed to be parametrically known or estimated from the values in the boundary array. The probability of false alarm, PFA, is given by

$$\text{PFA} = \int_T^\infty f(x)dx \tag{1}$$

According to equation 1, if the test pixel value is not smaller than T, then the probability of false alarm is not larger than its pre-defined value. Thus, for each position of the moving window, the value of T obtained by solving equation 1 can be taken as an adaptive threshold to decide whether the test pixel belongs to a target.

By exploiting ancillary information (sensing time, ground sample distance, radiometric resolution, spacecraft position and kinematics) provided by the sensors installed aboard the host spacecrafts, the algorithm produces full radiometric and geometric resolution crop files, in geotiff format. In order to provide the subsequent processing steps with an output result with proper coordinate system, a transformation from the UTM system to the Latitude/Longitude coordinate system is finally performed.

2.2 Ship fine segmentation

The recognition of visual attributes within the AoI allows the user to highlight relevant informative content in the data. Imaging algorithms are applied to extract geometric and radiometric features, which provide meaningful insights about the vessels morphology, geometry and dynamics. SAR images acquired by a satellite platform are often affected by distortions due to marine clutter, spectral leakage, or antenna sidelobes. These can mask the target image, thus hampering the possibility of evaluating the size and the behavior of the ship. An example of this type of distortions is represented in the Sentinel-I intensity image in figure 3, where the presence of a strong, cross-shaped artifact is apparent.

To the purpose of optimally identify the set of pixels belonging to the potential ship target, a dedicated segmentation module (SISS-Ship Image Segmentation from Space) has been developed. The main SISS features are here discussed, underlining the main differences w.r.t. previous approaches [5,6]. SISS accepts multi-sensor input data, such as SAR and optical images. In the case of SAR images, the algorithm processes the signal looking for strong reflectors, usually appearing as bright,w.r.t. the background, connected areas. In the case of optical

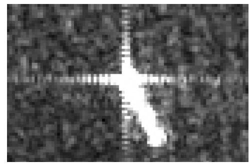

Fig. 3. Crop example of a SAR signal containing an individual ship candidate: a clearly visible cross-shaped artifact strongly affects the data quality.

images, the algorithm still looks for connected regions of outliers with respect to the background statistics, with the drawback that meaningful data can only be provided during daylight and under clear sky condition.

The first step of SISS consists in building a binary shape where the target pixels are set to 1 while the remaining pixels are set to 0. This is obtained through an adaptive thresholding approach. The employed threshold is a multiple integer of the standard deviation σ, computed from the whole input image I. Hence the threshold value has the following form:

$$\sigma_{th} = k\sigma. \tag{2}$$

k is set according to the following schema:

1. $i = 1, 2, \ldots$
2. define matrix I_t as
$$I_t = \begin{cases} 1 & \text{if } I \geq i\sigma \\ 0 & \text{elsewhere} \end{cases}$$
3. consider $\bar{i}$ as the smallest i such that I_t vanishes everywere.
4. $k = \bar{i} - 1$.

For each iteration, SISS estimates the ship footprint by simultaneously considering the signal amplitude and the interconnection between adjacent pixels. The estimated footprint also undergoes a fit process exploiting a parametric Ship Shape Model (SSM) that is defined *a-priori* by the user (e.g. an ellipse whose parameters are estimated on the image). At every iteration, the biggest connected area is computed and compared to the surface of the smallest SSM including such connected area. The algorithm finally returns the largest mask that better approximates the SSM.

After the thresholding stage, the target is isolated by clipping the image outside a mask including the ship and the possible artifacts. The subsequent step is to find the principal inertia axes by performing an eigenvalue analysis on the 2D inertia tensor, computed with respect to the barycenter of the thresholded image. Then a rectangular mask is applied around the barycenter, so as to include the whole target while cutting out part of the artifacts. By iterating this procedure, it is possible to perform a progressively refined estimation of the ship length overall (LOA), beam overall (BOA) and heading (see figure 4). Indeed, when no artifact is cut out anymore, we take the unit vector of the minimum inertia axis as the estimated heading, and the maximum distances between target boundary points along the principal axes as the estimated LOA and BOA. In the absence of further information, such as a detected wake or possible morphological ship features, the heading is estimated up to a 180^0 ambiguity.

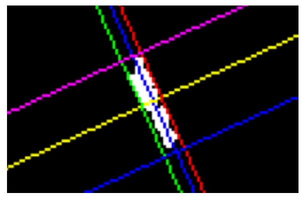

Fig. 4. Result of the ship segmentation algorithm applied to the SAR image crop in figure 3. The principal inertia axes and enclosing rectangle are highlighted in color.

2.3 Ship classification and identification

The information collected from the previous processing stages is exploited to perform a vessel classification, implemented by feeding a tailored classifier with the estimated features.

Classification and identification are not well defined in the literature. We choose to distinguish between them admitting that classification includes methods able to distinguish between a few classes of vessels, for example, fishing boats, tankers and container ships, while identification is just a finer classification, where the targets are assigned to a richer set of classes, in the limit, each including a single, well-identified vessel. Of course, more and more sophisticated features are needed to refine the classification, possibly including features that do not pertain strictly to the targets, such as wakes, and their influence in the overall performance is not independent of the chosen classifiers. For the purpose of the work described here, classification has been based on visual features that have relevant discriminative power, extracted from the captured SAR/optical images. For single-polarization, high-resolution SAR data, these can be based on simple geometric measurements. For example, the estimation of the length-to-width ratio, a standard indicator for ship structure [7], can be exploited to discriminate among target types, provided that the achieved accuracy is sufficient to get a reliable estimate.

Preliminary classification tests have been performed exploiting Automatic Identification System (AIS) data as a ground truth reference. These tests have been based on a decision-tree classifier. The availability of the ground truth allowed us to prove that the method is capable of identifying several ships categories such as fishing boats, tankers, and containers. Under these assumptions the algorithm classifies correctly in the 75% of the cases.

Aiming at increasing the performance of classification and identification methods, we have designed and developed a database system able to manage and correlate data from other sources (e.g. vessels databases) with the features extracted from the input images. By exploiting the database system, the classification and identification methods will be able to take into account any kind of additional feature extracted from both SAR and optical data, such as radiometric, polarimetric and color based features. The features extracted from new images will then be employed to perform similarity search operations to identify the possible class of the target based on the data stored into database.

2.4 Ship kinematics estimation

Previous research [8] provided a robust description of the physics underlying the wake pattern generation due to the ship passage through the water. Starting from this background, a main goal in the proposed maritime monitoring platform concerns the development of computational imaging procedures to provide insights about the ship kinematics through SAR imagery processing. [9,3,4].

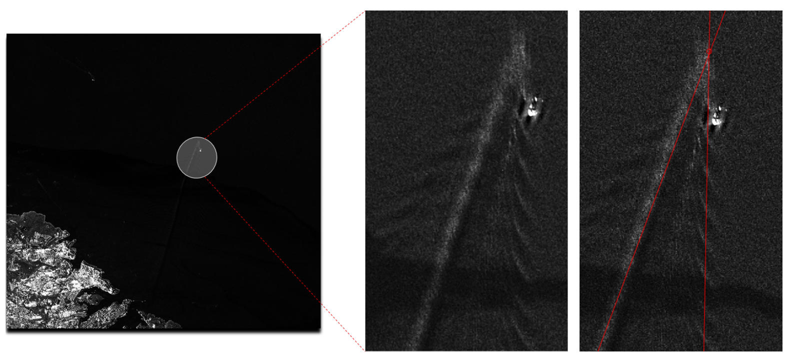

Fig. 5. Wake pattern detection.[3]

The wake results from multiple oscillatory components whose summation exhibits a V-shaped pattern centered on the ship route axis. The V angular aperture approximates a constant 39° value. Exploiting these observable phenomena, the route direction can be estimated by first detecting the V pattern (figure 5) through a Radon-transform linear detector [10], and later by identifying the wake center axis.

The wake pattern carries information about the vessel speed. Indeed, the oscillatory components observed in the external boundaries of the wake, feature wavelength values that relate to the velocity of the ship. Hence, provided the image resolution is large enough to observe these details, the Fourier analysis of a linear sample extracted from one Kelvin wake component (blue line in figure 6, upper left side) is performed. This allows to estimate the dominant wavelength λ (see lower left side in figure 6, with the spatial sampling on the right and the estimated power spectrum on the left) which is in turn employed to compute the ship's velocity v according to [9]:

$$v = \sqrt{\frac{\sqrt{3} g \lambda}{4\pi}} \tag{3}$$

where $g = 9.81\ m/s^2$.

A second method for vessel speed estimation exploits the azimuth shift effect, a distortion which affects SAR images, causing an artificial separation between the moving ship and its wake [11]. The separation length Δ_{as} is measured directly on the SAR map (red line in figure 6, right side) and employed to estimate the vessel speed according to:

$$v = \frac{V_{sat} \cdot \Delta_{as}}{R_{sr} \cos\beta} \tag{4}$$

where V_{sat} is the satellite speed, R_{sr} is the slant range from satellite to the target and β is the angle between the vessel's velocity vector and the azimuth direction. Figure 6 illustrates examples of the mentioned image processing methods.

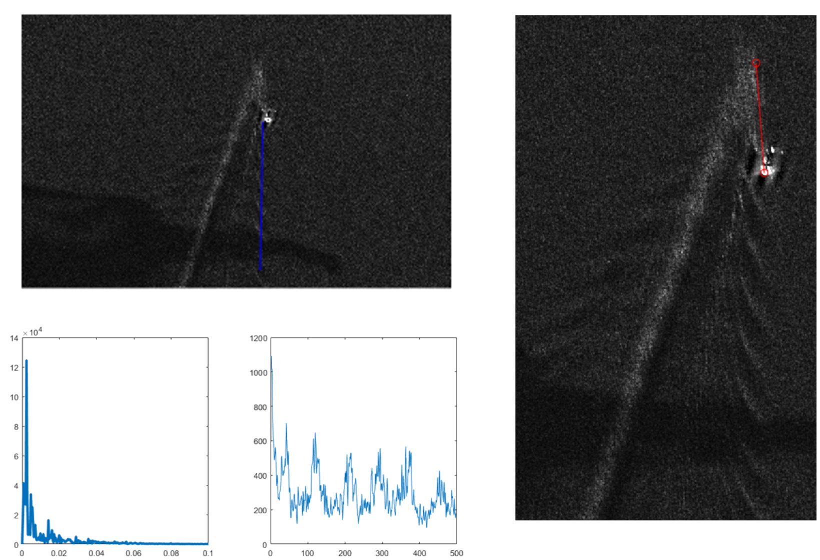

Fig. 6. External wake Fourier analysis (left) and azimuth shift (right).[4]

[4] COSMO-SkyMed Product – © ASI 2016 processed under license from ASI Agenzia Spaziale Italiana. All rights reserved. Distributed by e-GEOS

3 Implementation

OSIRIS[5] (Optical/SAR data and system Integration for Rush Identification of Ship models), an ESA project launched in February 2016, represents an effective implementation of the ideas and concepts described so far. Its main goal is the development of a platform dedicated to sea surveillance, capable of detecting and identifying illegal maritime traffic. At full operating conditions, the OSIRIS technological platform will be in charge of collecting and integrating data made available by multi-source, multi-sensor satellite missions for specific maritime areas of interest and processing the acquired data to detect and classify seagoing vessels. Crucial information for ship identification will be collected by means of popular ship monitoring systems (e.g. AIS) and by integrating additional information gathered from Open-Source Intelligence systems. The data will be finally analyzed to provide predictive models for the routes of these ships. AIS data will be provided by two different companies Astra Paging[6] (from ground based receivers) and Exact Earth[7] (from satellite constellations). A web GIS platform is currently in charge of collecting and fusing the AIS data coming from the two mentioned providers and, after a filtering stage to suppress fake or repeated records, making it available to the project operators.

4 Conclusions

A software platform dedicated to maritime traffic monitoring has been presented. The main goal of this platform is to detect and identify target vessels within a given sea surface area, which is remotely supervised by orbiting satellites such as Sentinel 1/2, CosmoSKy-Med and EROS missions. Radar and optical images represent the main input data for the described platform. These are processed by a suite of algorithms which are sequentially applied to the data returning information about i) the ship positioning within the inspected area, ii) the main ship geometrical attributes (length overall, beam overall, heading), and iii) the ship kinematics.

Future developments will be devoted to improve the overall performance of the platform by enhancing the accuracy of each individual stage in the processing pipeline and devising further classification methods. We observed that with particularly noisy or distorted images, the estimates returned by the implemented segmentation module are not sufficiently robust. We are studying to establish resolution and signal-to-distortion ratio requirements that are sufficient to guarantee a specified accuracy. We noted that the result often depends significantly on the initial shape assumed, that is, on the thresholding strategy. Without relying on supplemental data or preprocessing, we are now trying to find a method to suitably tune the thresholds. Our next attempts will be to integrate the results from the same target imaged through different transmit-receive

[5] https://wiki.services.eoportal.org/tikiindex.php?page=OSIRIS
[6] http://www.astrapaging.com/
[7] https://www.exactearth.com/

polarizations and integrate the extracted features in the classification process. Furthermore, this work is intended as a step towards a more complete ship classification method, also based on radiometric and/or polarimetric features, and a more reliable course and speed estimation, based on wake feature extraction and azimuth shift evaluation. Since wake patterns are hardly detectable in SAR maps, future developments will also be devoted to the refinement of the wake recognition process, based on the exploitation of additional information, such as the fine estimate of the vessel position as well as the theoretical constraints of this peculiar hydrodynamics problem (e.g. wake fixed angular aperture). The presented platform is being currently tested within the framework of the OSIRIS project, providing preliminary promising results from a real world testing workbench.

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