Abstract—Carrying out an effective control of fishing activities is essential to guarantee a sustainable exploitation of sea resources. As the regulated areas are extended, satellite-based Synthetic Aperture Radar (SAR) provides a powerful surveillance capability allowing the observation of broad expanses, independently from weather effects and from the day / night cycle. This paper proposes a novel approach for ship detection based on the analysis of oceanic SAR images by means of the wavelet transform. The analysis of the detection performance over both simulated and real RADARSAT SAR images confirms the robustness of the proposed method: ships, undetectable with other conventional techniques are noticeably sharpened, whereas background noise is drastically reduced.

Wavelet transform; edge detection; multiresolution analysis

I. INTRODUCTION

A large amount of investigations have proven that satellite-based SAR can be employed for ship detection purposes [1]. Particularly, in Europe, the project IMPAST (Improving Fisheries Monitoring by Integrating Passive and Active Satellite Technologies) aims at developing a pre-operational system for the control of fishing activities which combines information from satellite imagery and VMS (Vessel Monitoring Systems) while the DECLIMS (Detection and Classification of Marine Traffic from Space) project compares the performance of the existing tools of ship detection and classification from space [2]. Among the observations raised by the DECLIMS project reports, it should be pointed out that the present-day difficulties related to the detection algorithms make the operational use of satellite-based SAR techniques still quite limited: for some of the imaged regions during the IMPAST campaigns, automatic detection success is proved lower than expected. Hence, some efforts in order to overcome these unsatisfactory results have still to be furnished.

On the one hand, conventional ship detection algorithms, conceived to discriminate an exceptionally bright localized pattern, are based on the application of a threshold, calculated from an established noise model adapted to the statistical characteristics of a region of the image. Nevertheless, a suitable noise model is difficult to establish since numerous ocean surface features may alter it. Moreover, this reasoning relies on the existence of a considerable contrast between the vessels to be detected and the sea clutter, which is not always reached, e.g. wooden boats. These intuitive observations imply that it would be more effective facing the detection not only taking exclusively into account the intensity characteristics of the image but also studying its very localized statistical behavior.

On the other hand, the difficulties encountered by the existing near operational algorithms essentially are based on the automatization of the process of ship detection since, surprisingly, undetected vessels are sometimes visible by eye. The human visual system performs simultaneously over the observed scene a selective filtering in frequency and in orientation and it is able to focus on different elements at different scales.

Therefore, multiresolution analysis with wavelets seems to be a suitable tool for modelling the operation of the human vision, while providing a localized statistical study, too.

II. WAVELET SUBBANDS CORRELATION APPLIED TO SHIP DETECTION: THEORETICAL PRINCIPLES

A. Multiresolution Analysis with the Wavelet Transform

The Wavelet Transform (WT) proposes boarding the study of a complex phenomenon, dividing it into different simpler pieces (1).

\[ Wf[n, a'] = \sum_{m=0}^{N-1} f[m] \psi_j[m-n] \]  

being \( f \) the discrete signal and \( \psi_j \) a discrete wavelet atom.

This means projecting it in a particular function space in which it is located in the wavelet space by measuring its degree of similarity with each basic function. In a WT, the basis functions come from dilations and translations of a “mother wavelet”, \( \psi \), localized in both, time and frequency (2).

\[ \psi_j[n] = \frac{1}{\sqrt{a'}} \psi\left(\frac{n}{a'}\right) \]  

Each term of the basic, therefore, allows the representation of the signal at a given scale and so a WT can focus on structures with a “zooming” procedure [3]. In 2D, a wavelet
basis is constructed with separable products of a scaling function and a wavelet. Three wavelets are then defined, each of them extracting details at different orientations.

B. Singularity detection with the wavelet transform

By decomposing signals into elementary building blocks that are well localized in space and frequency, the WT can characterize the local regularity of signals. It is well known that the WT of a function at a point depends on the degree of variation of the values of the function in a neighborhood of this point, whose dimensions are proportional to the scale. More specifically, the modulus of the WT at a scale can be viewed as the derivative of the signal smoothed at this scale and so the existence of discontinuities in the original image will produce large wavelet coefficients. On the contrary, regular areas will be represented by small coefficients in the wavelet domain. Fig. 1 shows the first, the third and the fifth iterations of the discrete WT with Haar coefficients – the most suitable for the detection of very sharp variations - of a pulse – coarsely approximating the response of a ship -.

Fig. 1 reflects two interesting points. On the one hand, the approximation coefficients of the WT of the pulse represent a pulse, tighter and higher with the increase of the number of iterations – ideally tending to a delta -. On the other hand, large detail values mark the presence of a discontinuity. It should be pointed out that when the scale becomes coarser, the two maxima combine themselves. The proposed algorithm for ship detection plans on taking advantage of this fact performing the detection of a target through its contour.

Moreover, in 2D, the operation of derivation performed by the WT is spatially localized so that each detail subband enhances edges in a particular direction: horizontal, vertical and diagonal as it can be seen in Figs. 2 and 3.

C. Spatial correlation of the wavelet subbands

The method proposed in this paper for ship detection in SAR imagery by means of the WT is mainly inferred from the considerations presented above and from the observation of the difference of statistical behavior between the vessels and the surrounding sea [4]. More specifically, the interesting point here is to characterize this difference of statistical behavior in the wavelet domain. When the WT is applied to image processing, it is usually assumed that the subbands are uncorrelated. However, it has been shown that the wavelet coefficients may have some dependencies due to regular spatial structures. So, attending to this particular property of the WT, the algorithm consists on spatially correlating the four...
subbands obtained after the application of the WT. Nevertheless, as the goal here is to detect a localized irregularity, the information contained in the detail subbands is very helpful in this case.

On the one hand, a vessel behaves as a deterministic target. As its response should be approximated as a short pulse, it will present frequencial components in every subband obtained after the application of the 2D WT (see Fig. 3) and it can be noticeable in every subband. Intuitively, pixels constituting a ship are intimately related, as they belong to the same structure, with proper intensity and statistical characteristics, so that the correlation operation after the application of the WT will stand out these deep relations. As a consequence, the presence of the ship will be enhanced.

On the contrary, pixels constituting the background noise are randomly distributed and, thus, the correlation applied will produce reduced values, attending to the poor probability of coincidence of related coefficients.

III. EXPERIMENTAL RESULTS

The proposed algorithm has been tested over a set of real RADARSAT SAR images (acquired in ScanSAR mode, with a resolution of 50 m.) as well as over a simulated image, representing awkward situations for detection in which conventional algorithms based on the application of a threshold fail [2].

In order to quantify the difficulty of performing a correct detection a contrast parameter, $CI$, is defined as the ratio of the difference between the mean of the intensity of the pixels belonging to the ship and those of the surrounding sea by the dynamic range of the fragment of image considered (3).

$$CI = \frac{\text{in}_{\text{ship}} - \text{in}_{\text{neigh.}}}{\text{dynamic \_range}}$$

The algorithm is first checked on a simulated image (see Fig. 4) presenting a small vessel (5 px.) with a very low contrast. After the application of the DWT with Haar coefficients, four components are obtained (Fig. 5) in which the vessel is not visible. Finally, those four components are spatially correlated and, as a result, the presence of the target is now clearly appreciable (Fig. 6) and the background noise has been considerably removed. Another aspect is the enlargement on the dynamic range, which will facilitate the decision rules.

The algorithm is then tested over real RADARSAT images in which the presence of the ships is known through reported VMS positions synchronized with data acquisition. Some illustrative examples are presented hereafter.

First, the method is tested on a fragment of RADARSAT image with a ship presenting a very low contrast in front of the surrounding sea (available groundtruth). This ship is not detected with conventional operational systems [2], but after the application of two iterations of the algorithm proposed in this paper, the presence of the ship is notorious (see Fig. 7).

$$CI = \frac{\text{in}_{\text{ship}} - \text{in}_{\text{neigh.}}}{\text{dynamic \_range}}$$

Figure 4. Fragment of a simulated image (128x128 px) presenting a small ship (5 px.) marked with a white circle, with a very low intensity (3 times the mean of the image). $CI=0.56$.

Figure 5. Four components resulting from the application of one iteration of the DWT with Haar coefficients to the simulated image presented on Fig. 4. It may be observed that the target is visible in none of the subbands.

Figure 6. Result of the correlation of the four components obtained after the application of one iterations of the DWT. The presence of the ship is greatly enhanced, while noise is drastically reduced ($CI=0.99$).

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Figure 7. Application of the proposed algorithm on a fragment of real RADARSAT image (128x128 px). On the right, original image ($CI=0.65$); on the left, result of the application of the algorithm ($CI=0.97$).
Another difficult situation for detection is when the ship is placed on an inhomogeneous background (Figs. 8 and 9). The following image (Fig. 8) presents a very small ship in a particularly noisy background, with vertical stripes due to marine features.

Figure 8. Application of the proposed algorithm on a fragment of real RADARSAT image (128x128 px). On the right, original image (CI=0.70); on the left, result of the application of 2 iterations of the algorithm (CI=0.97).

Finally, an interesting feature of the algorithm is the separation of the targets according to their characteristics. The last example presents a fragment of real RADARSAT image with two ships (Fig. 10). One of them (bottom left of the image) is easily detectable by means of conventional techniques. The second one (centered in the image) presents a very low contrast (2.6 times the mean of the image) and, hence, it is not seen by traditional algorithms. When applying the method proposed in this paper the two ships are separated, thanks to the multiresolution capability of the WT, and so each vessel is detected with a different number of iterations (when the scale is the most suitable to its size) (see Fig. 11).

Figure 9. Application of the proposed algorithm on a fragment of real RADARSAT image (128x128 px). On the right, original image (CI=0.49); on the left, result of the application of 1 iteration of the algorithm (CI=0.99).

Figure 10. Fragment of real RADARSAT image (128x128 px) with two ships (CI=0.92 for the brighter one and CI=0.18) (groundtruth is available).

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Figure 11. Result of the application of the proposed algorithm after 2 (left) and 3 (right) iterations. CI=0.99 for the two cases.

IV. CONCLUSION
A novel ship detection algorithm based on the wavelet theory has been presented in this paper. By the spatial correlation of the subbands obtained after the application of the DWT, the presence of a ship can be enhanced, whereas noise is drastically reduced and the dynamic range is enlarged for a more effective performance of the decision rules. The algorithm has been successfully tested over a set of real and simulated images and it presents some other interesting features to be exploited in the future.

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