ADVANCED SHIP DETECTION FOR SPACEBORNE BASED MARITIME AWARENESS

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ABSTRACT

In the last years the increase in marine traffic generated the necessity of global monitoring for marine environment management in terms of safety, security and fisheries.

The increasing number of new satellite-based Synthetic Aperture Radar (SAR) systems, and the intrinsic capability of the transmitted electromagnetic pulses to interact with the ships and to retrieve its cinematic characteristics, made this instrument particularly fit to improve global maritime awareness through the fusion with cooperative data (AIS, VMS, LRIT).

The growing need of global maritime awareness gave a push to the realization of different projects in the European context, each one focused on a different particular objective.

Particularly useful is the synergy between the operational and research aspects, being the goal of the last to improve the state of the art in the field of ship detection. Two European projects are the key to strive this synergy: the project MARitime Security Service (MARISS), which implements the operational capability, and the R&D Dolphin projects, which is focused on the deep exploitation of remote sensing data and on the technological development of advanced techniques for ship detection and classification purposes, and Seabilla project, which is also dedicated to improve the current ship detection capability and to fuse all the available information from different data sources for border surveillance optimization.

This paper introduces the multipurpose Edisoft Vessel Detection software (EdiVDC) implemented by the EDISOFT company, which comes from the necessity to respect increasingly stringent requirements in terms of ship detection.

The EdiVDC software is being operationally used in the framework of the MARISS project and it integrates advanced processing algorithms, developed in the scope of the Dolphin project with the cooperation of ISEL-IT (Instituto de Telecomunicações), and data simulators, developed in the context of the Seabilla project, improving the software capability and introducing new functionalities.

In this work we present the functionalities of the software and the main results achieved with different types of SAR data.

1. INTRODUCTION

The SAR plays a very important role in the ocean monitoring, particularly in ship detection, in which the SAR is particularly fit for its intrinsic capability in commercial, surveillance and strategic context.

After several years since the launch of operative projects for ship detection purposes, as MARISS, the SAR data informative content was exploited and many algorithms were proposed.

Currently, the acquired maturity allowed the definition of more stringent requirements, with the aim to maximize the informative content; particularly, the key maritime surveillance requirements that should be obtained in the context of the current projects are:

- the capability to detect small and fast boats;
- the capability to track the targets of interest in open seas;
- the capability to characterize the detected targets in terms of geographical position, size, velocity and ship class;
- the capability to discriminate potential illegal activities through anomalous behaviour analysis;
- the capability to simulate scenario's ad hoc for the demonstration of discriminate potential illegal activities through anomalous behaviour analysis.

In consideration of the aforementioned requirements, the Edisoft VDC was implemented integrating different useful tools for maritime monitoring, exploiting all the SAR data types and the processing algorithms.

Particularly, the implemented modules of the VDC software in maritime surveillance for ships monitoring purposes are the following:

1. Ship detection;
2. Ship classification (velocity estimation);
3. SAR data simulation of ships in maritime environment.

The proposed modules are integrated in the same platform, allowing the synergy between detection techniques (working on different data types) and data simulation, with the purpose of algorithm testing and validation and of simulated scenario's building: this validation is essential for the success of the high level border surveillance and maritime activities architecture validation in the context of the Seabilla project.

This paper is organized as follows.

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In section 2 the VDC software is introduced with its working scheme. In section 3 the ship detection and classification algorithms are presented, considering the techniques working on multilook data (subsection 3.1) and on SLC data (subsection 3.2 and 3.3).
The section 4 is dedicated to the implemented simulators that are able to generate simulated Single Look Complex (SLC) data (subsection 4.1) and multilook data (subsection 4.2).
Finally, the conclusions and the future work are described in section 5.

2. VDC SOFTWARE ARCHITECTURE

The VDC software is divided into five groups:
1) Data Import
2) Detection and Classification
3) Sub-Aperture Processing
4) Data Simulation
5) Auxiliary Tools

2.1. Data Import

This group is responsible for reading and preparing SAR data for processing. It can read data from ERS2, Envisat, RS1 and RS2 satellites. After reading the image data and its complementary information a land mask is computed and applied based on external coastline information.

2.2. Detection and Classification

This group is responsible for running the vessel detection and classification algorithms on multilook images. There are two ship detection algorithms that can be applied alone or together for a more robust detection. Features are extracted from the resulting detections and a ship velocity estimation algorithm, based on the distance from the ship to its wake, is applied.

2.3. Sub-Aperture Processing

This group is responsible for running the vessel detection and classification algorithms on complex images. It can be applied on a single tile for evaluation purposes or for the entire image.

2.4. Data Simulation

This group is responsible for generating complex or multilook simulated data. This data can then be used for demonstration purposes or algorithm performance evaluation.

2.5. Auxiliary Tools

Consists in a group of operations such as loading and presenting AIS data in the SAR image; correlation between detections and AIS data; report and kmz generation, etc…

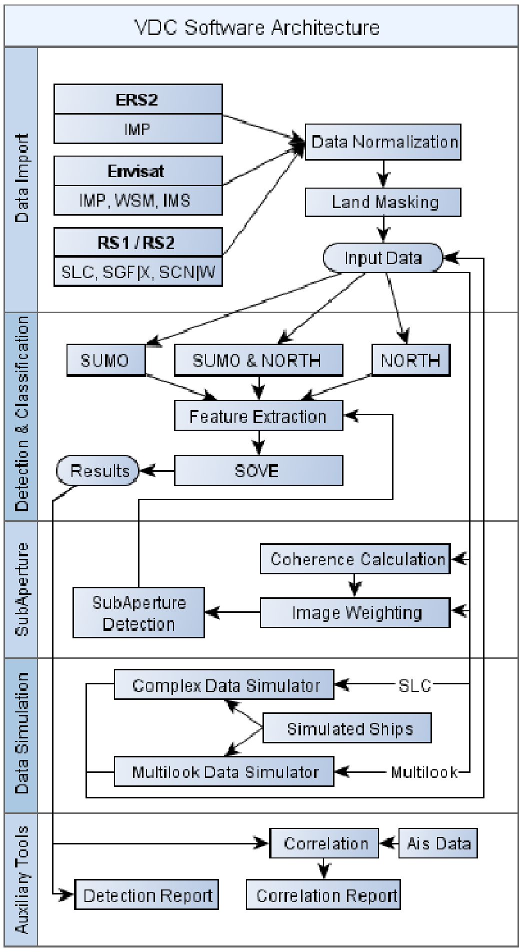

Figure 1 – VDC software architecture

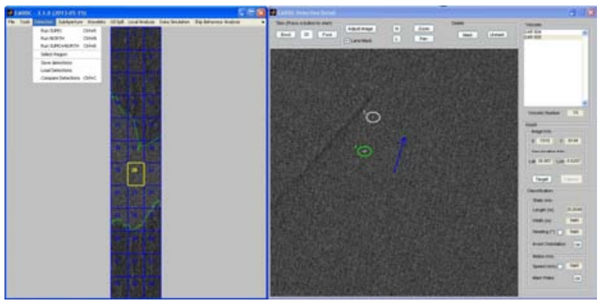

Figure 2 – VDC software graphic user interface

3. SHIP DETECTION AND CLASSIFICATION

Most of the ship detection algorithms applied on an operative base use L1B data (multilook data), that provides only the amplitude information [1]. The amplitude data provide information about the ship backscattering integrated during the synthetic aperture generation.
Other algorithms work on complex data (L0 -raw data- or L1A - SLC data) and most of them use the coherence concept for increasing the detection probability.
In the next subsections the algorithms working on multilook data and SLC data will be presented.

3.1. Algorithms working on multilook data

The VDC implements two detection algorithms for ship detection and one algorithm for velocity estimation.

3.1.1. Ship detection algorithms

Two ship detection algorithms were implemented in the VDC software, called respectively SUMO and NORTH.

<u>*SUMO ALGORITHM*</u>

The first approach that Edisoft used for ship detection is called SUMO (Search for Maritime Unidentified Objects) [2].
The SUMO algorithm is based on the knowledge of the compressed IRF (Impulse Response Function) of a target, which is represented by a bidimensional sinc function [3].
The working mode of the algorithm can be reassumed:

1. The image is divided in tiles;
2. For each tile the land masking is performed and the statistical information (the mean μ and standard deviation σ) is retrieved.
3. The mean and the standard deviation are used to build a template moving window that is applied to each valid pixel in the tile.
   Let k1, k2 and k3 be three constants; the three adaptive thresholds used by SUMO are the following:
   $$\begin{cases} T_1 = \mu + k_1 \cdot \sigma \\ T_2 = \mu + k_2 \cdot \sigma \\ T_3 = \mu + k_3 \cdot \sigma \end{cases} \quad (1)$$
   with $k_1 > k_2 > k_3$.
   Different moving windows generated by the thresholds are used, depending on the data type and on the spatial resolution. The moving window consists of a high threshold core (*T1*) surrounded by pixels with lower thresholds values (*T2* greater than *T3*). This pattern intends to replicate a vessel spectral signature over sea background.
   The two window types that are applied have the aim to detect respectively small/medium vessels and medium/big vessels:
4. The moving window is correlated to each pixel with value ≥T1; if the surrounding pixels have values greater than the respective thresholds T2 and T3, the pixel is classified as ship. Note that the constants k1, k2 and k3 are found empirically to increase the number of detected ships avoiding excessive number of false alarms. Note that the empirical constants were calibrated for each sensor and acquisition mode.

A clustering technique is then applied on the detected pixels to group the pixels that belong to the same ship.

<u>*NORTH ALGORITHM*</u>

The second approach used for ship detection is called NORTH (Normalized Threshold), a simple in-house developed detection algorithm.
This algorithm was originally designed for ship detection in Envisat Wide Swath Mode images, where the image intensity value was strongly dependent on range, i.e., near range was brighter than far range.
The algorithm takes into consideration the following assumptions:
a) sea pixels intensity can be decomposed in range and sea state dependent intensities
b) range dependent intensity is the same for all pixels in the same column (approximately the same range)
To detect possible ship pixels, the NORTH algorithm executes 3 steps:
1) A land mask is obtained for the corresponding SAR data
2) Taking into account only the sea pixels, the mean and standard deviation are computed for each data column
3) A pixel is considered as a possible ship pixel if:

$$\frac{p(r,c) - \mu(c)}{\sigma(c)} > T_S^I$$

where
p(r,c) is the pixel at row *r* and column *c*;
μ(c) is the sea pixels column mean;
σ(c) is the sea pixels column standard deviation;
T_S^I is an empirical threshold that depends on image type *I* and sea state condition *S*
The resulting ship pixels can then be clustered using different techniques, such as a simple *close* morphological operation.
This algorithm takes only 3.8s in a 5512x5579 Envisat WSM image and 6.1s in a 6374x8778 Radarsat-2 SGF image to run, in a Pentium 4 3GHz CPU with 2GB RAM and, although initially developed for Envisat WSM images, it performs well in other sensor systems and modes to detect pixels belonging to ships.
The main advantages of this algorithm are its simplicity, speed, low memory consumption, parallel processing capability and excellent results on along column uniform sea pixel intensities, while its main disadvantages come from along column non-uniformity sea pixel intensities, such as: few sea pixels for computing statistics; sea artefacts such as rain cells; region of rough sea in a major calm sea image; etc…

3.1.2. Ship classification algorithms

For each detected vessel the software activates a classification routine that calculates size and heading (if possible) and the velocity.
The only possibility to estimate the velocity in amplitude data is to calculate the Doppler shift due to the ship range velocity, which causes the well known azimuth shift of the moving target. The Doppler shift

can only be estimated if the ship wake is visible, calculating the distance between the moving target (ship) and the stationary target (wake) ([4], [5]).
The implemented method follows the so called SOVE algorithm (from Ship Orientation to Velocity Estimation), which allows the full velocity vector estimation if the wake is visible [6].
The method is based on the Radon Transform, which is a powerful mathematical instrument for line parameter extraction in images even in presence of noise.
The working mode of the algorithm can be reassumed:

1. A data tile is taken with the detected ship at the center.
2. As optional step, a directional filtering could be applied. The SOVE is implemented in the frequency domain and its main purpose is to select only the frequencies relative to the linear structures, reducing the influence that the pseudo-structures in the image can have in the wake detection.
3. The Radon transform is used to detect the wake scanning the space taking into account the ship orientation. Considering the fig. 2, the ground range velocity and the azimuth velocity result:

$$\begin{cases} v_{gr} = \lambda f_R \delta \big/ 2 v_B \sin \phi \\ v_{az} = v_{gr} \tan(\pi/2 - \theta) \end{cases} \quad (2)$$

where λ, f_R, v_B, Φ are respectively the radar wavelength, the Doppler rate, the ground beam velocity and the signal incidence angle.

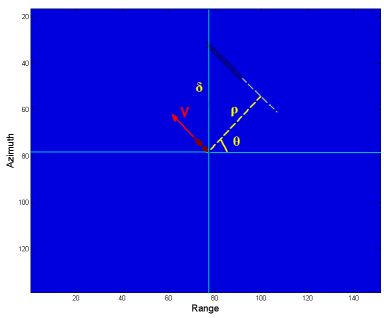

Figure 3 – SAR geometry if a ship and its wake

3.2. Algorithms working on Single Look Complex Data

The VDC implements an advanced ship detection algorithm, based on the sub-aperture processing, developed in the scope of the Dolphin project by Edisoft and ISEL-IT.

3.2.1. Ship detection algorithm: sub-aperture processing

The ship detection algorithms that work on amplitude images have some limitations that reduce the detection probability. In fact, often the ships and the boats could disappear from the image due to their reduced size or due to complex meteorological conditions that increase the sea clutter.
If the amplitude information provides the ship backscattering generated during the integration time, it does not provide any information about the temporal behaviour of the interaction between transmitted pulses and target, depending on the aspect angle and the speckle phenomenon.
To overcome these limitations, one can use complex data which should be processed using other methodologies [1].
In the context of the Dolphin project an advanced algorithm based on sub-aperture combination was proposed with the aim to calculate the coherence such that it can be used in operational contexts for the detection of ships and small boats, even if in complex meteorological conditions.
The coherence calculation through sub-aperture focusing is the best way to estimate the backscattering variation during the synthetic aperture, because a target could show different backscattering depending on the look angle.
The sub-aperture processing allows the focusing of different Doppler spectrum portions. Each focused look corresponds to different temporal centre and Doppler centroid. By combining different looks the ship detection performance can be increased through coherence calculation capability ([7], [8], [9]).
Particularly, this technique is based on the behaviour difference between the incoherent sea (observed as surface in continuous motion) and the coherent ship: in the sea surface the backscattering coefficient varies during the integration time, characterizing its incoherence, while the backscattering coefficient change of the ship is relative slow. In fact, it must be note that the coherence degree of a ship is decreased by its motion and the variation of the backscattering coefficient with the aspect angle and the view angle; nevertheless, the variation of the backscattering is slower comparing with the sea during the integration time.
Note that the sub-aperture processing could be performed with raw data (L0) or SLC data (L1A); we focused the attention on the SLC processing, considering that currently no raw data are available from the existing SAR systems.
The SLC data contain complex values that are acquired on the slant range plane and processed using the entire Doppler band available.
The sub-aperture generation with SLC data is performed in the following steps, as shown in fig. 4.

1. Auxiliary data and processed parameters importing from L1A file;
2. Complex SLC data reading;
3. Calculation of the compensated and compressed Doppler spectrum;
4. Spectrum Shift to Doppler Centroid

5. Azimuth de-compression of the data using the estimated Doppler parameters (optional);
6. Doppler spectrum filtering for sub-aperture generation;
7. Sub-aperture azimuth compression (only if step 5 was performed);
8. Compensation of the azimuth antenna pattern by removing the used weight filters (Hamming, Kaiser).
9. Focused data generation.
10. Combination of sub-aperture data for coherence calculation.

Ship detection on the original image weighted by the retrieved coherence.

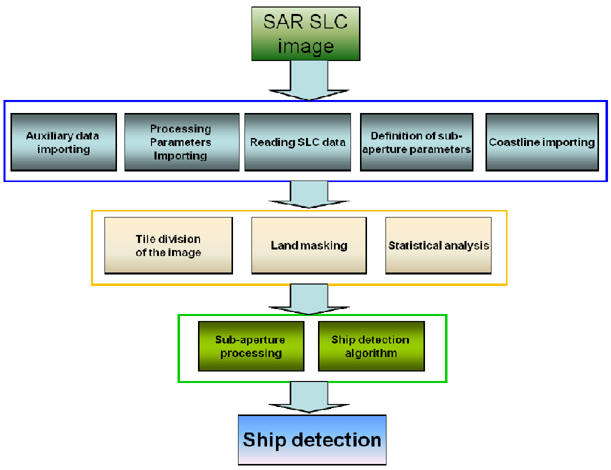

Figure 4 – Sub-aperture processing scheme

For the dedicated sub-aperture combination we decided to use three different portions of Doppler spectrum partially overlapped. This gives to us the possibility to filter the data without losing coherence due to the ship motion.
Let's consider the sub-apertures L_1, L_2 and L_3 of the complex image *I*. The data filtering is given by using the interferometric concept to the different looks:

$$I^* = I \cdot \left| \sqrt{\mathbf{L}_1 \cdot \mathbf{L}_2^*} + \sqrt{\mathbf{L}_1 \cdot \mathbf{L}_3^*} + \sqrt{\mathbf{L}_2 \cdot \mathbf{L}_3^*} \right| \quad (3)$$

Note that the selected look bands are overlapped to avoid problems of coherence loss due to the target motion and to avoid the excessive spatial resolution decreasing.
The sub-aperture processing allows the clutter filtering through the weighting of the coherence information.
Table 1 shows the results obtained with four ships in terms of Signal to Clutter Ratio (SCR); the last column indicates the SCR increasing using the sub-aperture processing algorithm.

Table 1. SCR improvement of the sub-aperture algorithm

Ship N°	SCR of SLC data (dB)	SCR of look combination (dB)	Differential SCR look combination-SLC (%)
1	25.7	46.8	82.1
2	16.8	31.4	86.9
3	31.6	59.7	88.9
4	17.7	28.8	62.7

Fig. 5 shows an example of sub-aperture processing in presence of a ship.
After the sub-aperture processing, that provided the filtered image *I*, the detection step must be applied.
Considering that the sub-aperture algorithm was implemented with the aim to detect small boats, it was decided to use a single adaptive threshold on the image weighted by the coherence.
Particularly, the threshold depends on the statistical parameters (the mean μ and standard deviation σ) and on an empirical constant.

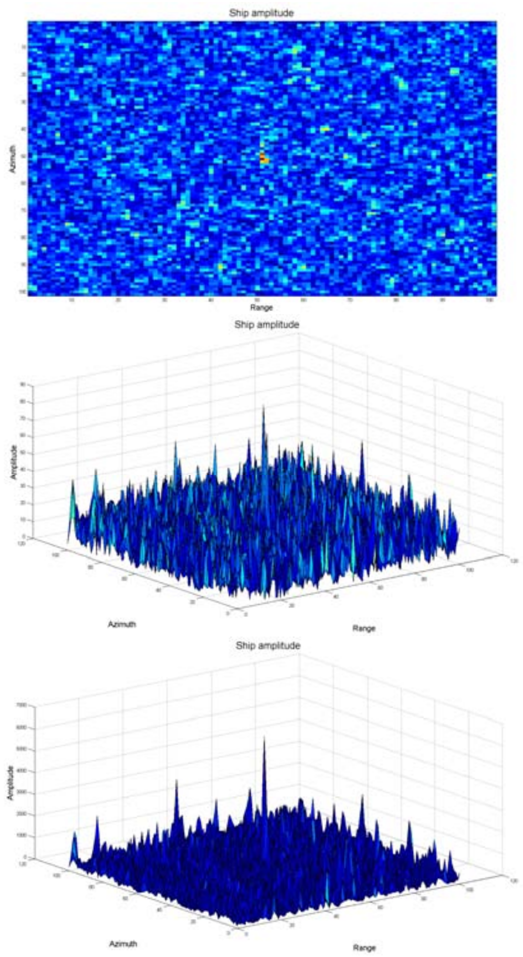

Figure 5 – SLC amplitude image of the ship (top), 3D SLC amplitude (center) and 3D filtered image (down)

The working mode of the detection algorithm can be resumed as follows:

1. The image is divided in tiles;

2. For each tile the land masking is performed and the statistical information (the mean μ and standard deviation σ) is retrieved.
3. The mean and the standard deviation are used to build the threshold.

   The adaptive threshold is the following:

   $$T = \mu + (k/R) \cdot \sigma$$

   where k is an empirical constant and $R = \mu/\sigma$ is the ratio between mean and standard deviation.

   Finally, the threshold becomes:

   $$T = \mu + k \cdot \sigma^2/\mu . \qquad (4)$$

4. SAR DATA SIMULATORS

A SAR data simulator is a useful tool for the validation of SAR parameter estimation algorithms, focalization techniques and dedicated processing ([10]-[12]).

Note that the main purpose of the simulated data is to complement the real data for algorithm development and demonstration building, maximizing the understanding of the SAR data informative content.

In this paper we propose two SAR data simulators that are able to insert simulated moving ships in the real data, following the approach in [12].

4.1.1. SLC SAR data simulator

The simulator is able to insert the raw data of the moving ships in the raw data obtained through bidimensional defocusing.

The simulator working steps are the following:

1. The SLC data are defocused in range and in azimuth through the respective reference functions used for the focalization. The raw data with range migration compensation are obtained.
2. The raw data of the moving targets are generated, following the method proposed in [12], and inserted in the raw data obtained in the previous step.
3. The SLC data are focused using the same reference functions mentioned in step 1.

Fig. 6 shows the general processing scheme of the simulator, while fig. 7 illustrates an example of simulation.

The inserted moving ships are generated considering the following assumptions:

- the ship is represented as rectangular object, characterized by the length and width (specified by the user);
- The slant range geometry is used;
- The Radar Cross Section (RCS) of each pixel pertaining to the ship is weighted by the percentual coverage of the ship in the pixel area;
- The RCS is constant during the integration time;
- The velocity is constant.

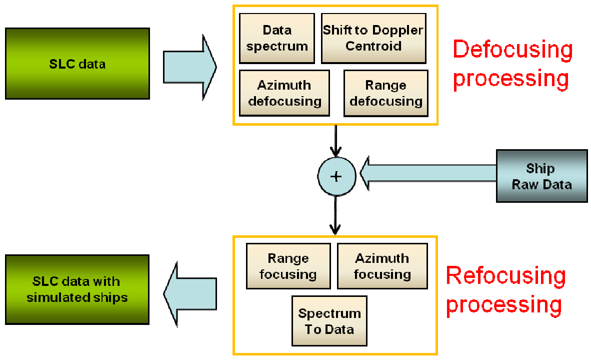

Figure 6 – SLC SAR data simulator scheme

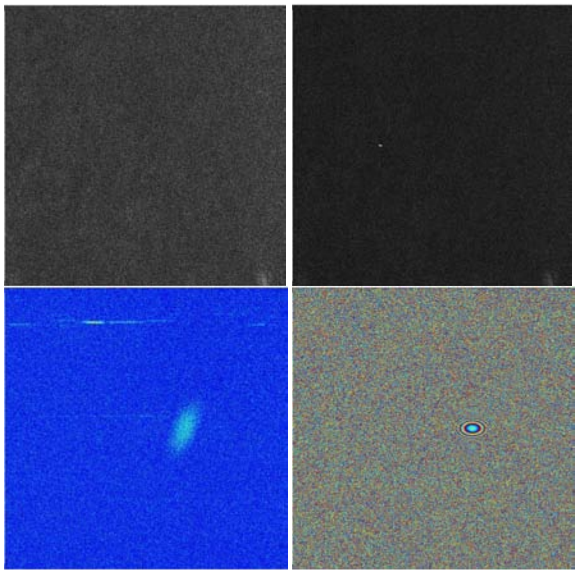

Figure 7 – Example of ship data insertion in SLC data. Starting from top-left in clockwise: 1) Original image; 2) Image with the simulated ship after the refocusing; 3) Phase image with the inserted ship raw data; 4) Amplitude image with the inserted ship raw data

4.1.2. Multilook SAR data simulator

The simulator follows the same scheme of the SLC SAR data simulator, but only the amplitude information of the moving target is inserted in the data.

The simulator working steps are the following:

1. The raw data of the moving targets are generated with the range and azimuth reference function. The range and the azimuth reference functions are used to focus the moving targets.
2. The amplitude of the focused target is inserted in the image.

Fig. 8 shows the general processing scheme of the simulator.

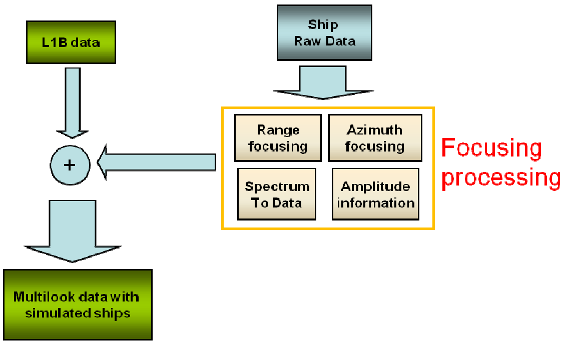

Figure 8 – Multilook SAR data simulator scheme

The inserted moving ships are generated considering the same assumptions of the SLC data simulator: the only one different assumption is the used geometry, that in this case is the ground range geometry instead the slant range geometry.

5. CONCLUSIONS AND FUTURE WORK

The presented VDC software is a multi-purpose tool for ship detection and classification. It was developed by Edisoft integrating the new algorithms developed in the scope of the projects Dolphin (in collaboration with ISEL-IT) and Seabilla, with the aim to realize a very useful tool in maritime surveillance for working in operational context.

Some activities are foreseen in the next future for validation and integration purposes; in particular, the following activities are planned.

- Integration of new SAR systems ingestion.
- Validation of the implemented algorithms used in operational projects.
- Implementation of dedicated data spectrum analysis algorithms for velocity estimation in SLC data.
- Implementation of more complex moving target simulation, considering non-linear velocity, backscattering change during the integration time and ship representation as more complex object.

6. ACKNOWLEDGMENT

The VDC software was implemented in the context of the MARISS, DOLPHIN and SEABILLA projects, thanks to which Edisoft acquired knowledge and experience on spaceborne based maritime awareness.

7. REFERENCES

1. Crisp, D.J., *The state-of-the-art in ship detection in synthetic aperture radar imagery*, DSTO–RR–0272, Defence Science and Technology Organisation, Edinburgh, South Australia, Australia, 2004.

2. Schwartz, G., Alvarez, M., Varfis, A., Kourti, N., *"Elimination Of False Positives In Vessels Detection And Identification By Remote Sensing"*, Proceedings of the IEEE Int. Geoscience Remote Sensing Symposium, IGARSS, Vol.1, pp.116-118, 24June-28 June 2002

3. Cumming, I.G., Wong, F.H., *Digital Signal Processing of Synthetic Aperture Radar Data: Algorithms and Implementation,* Artech House, January 2005.

4. Tunaley, J.K.E. , *The estimation of ship velocity from SAR imagery*, Proceedings of the IEEE Int. Geoscience Remote Sensing Symposium, IGARSS, Vol.1, pp. 191-193, 21-25 July 2003.

5. G.Zilman, G., Zapolski, A., Maron, M., *The Speed and Beam of a Ship From Its Wake's SAR Images*, IEEE Trans. on Geoscience and Remote Sensing, Vol.42, n.10, pp.2335–2343, Oct 2004.

6. Radius, A., Marques, P., *A Novel Methodology for Full Velocity Vector Estimation of Ships Using SAR Data*, Proc. Of the 7th European Conference on Synthetic Aperture Radar, EUSAR´08, 02-05 June 2008.

7. Arnaud, A., *Ship Detection by SAR Interferometry*, Proceedings of the IEEE Int. Geoscience Remote Sensing Symposium, IGARSS, Vol.5, pp.2616-2618, 28 June-2 July 1999.

8. Ouchi, K., Tamaky, S., Yaguchi, H., Lehara, M., *Ship detection based on coherence images derived from cross correlation of multilook SAR images*, IEEE Geoscience and Remote Sensing Letters, Vol. 1, Issue 3, pp. 184–187, July 2004.

9. Brekke, C., Anfinsen, S. N., Larsen, Y., *A study of sublook extraction strategies in ship detection with the sublook correlation magnitude*, IEEE Geoscience and Remote Sensing Letters, vol. 10 Issue 4, pp. 786-790, Dec. 2012.

10. Bamler, R., Runge, A., Steinbrecher, U., *A Distributed Target SAR Raw Data Simulator with arbitrary Doppler Variation*, Proceedings of the IEEE Int. Geoscience Remote Sensing Symposium, IGARSS, pp. 287-290, 26-29 May 1992

11. Franceschetti, G., Migliaccio, M., Riccio, D., Schirinzi, G., *SARAS: A Synthetic Aperture Radar (SAR) Raw Signal Simulator*, IEEE Transactions on Geoscience and Remote Sensing, Vol. 30, Issue 1, pp. 1238–1244, Jan 1992

11. Radius, A., Marques, P., *Synthetic Aperture Radar Raw Data Simulator for Sea Environment Dedicated to Moving Ship Detection*, Proc. Of Sensor Signal Processing for Defence Conference, SSPD 2012, 25-27 September 2012.