ISAR MODE FOR COSMO SKYMED SYSTEM WITH SUPER-RESOLUTION OPTIONS: ICOSSOP PROJECT

Alessio Bacci (1), Fabrizio Berizzi (1), Flavio Fico (2), Elisa Giusti (1), Pierfrancesco Lombardo(2), Marco Martorella(1), Debora Pastina(2), Rossi Rainer Maria(2)

(1) University of Pisa, Department of Information Engineering, via Caruso 16, 56122, Pisa, Italy
(2) University of Roma "La Sapienza", Department DIET, via Eudossiana 18, 00184 Roma, Italy

ABSTRACT

The aim of this paper is to describe the activities related to the project "ISAR mode for COSMO SkyMed system with super-resolution options: ICOSSOP". The project has proposed an innovative use of COSMO Skymed data and specifically the development of an Inverse Synthetic Aperture Radar (ISAR) mode with super-resolution options. The goal was to reconstruct high resolution and well focused ISAR images of moving targets extracted from a Synthetic Aperture Radar (SAR) scene. In this paper the developed techniques for automatically detecting and refocusing moving targets starting from satellite Single Look Complex (SLC) SAR images will be described and results will be shown.

1. INTRODUCTION

The aim of this paper is to describe the activities related to the project "ISAR mode for COSMO Skymed System with Super-Resolution Options (ICOSSOP)" funded by the Italian Space Agency (ASI) under the framework of the first Announcement of Opportunity (AO) for the exploitation of COSMO Skymed data. The project took two years and was carried out by two Italian Universities, namely the University of Pisa (Department of Information Engineering, Radar Laboratory), as principal investigator, and the University of Rome "La Sapienza" (DIET Department). The team was composed of full and associate professors, researches and PhD students who work actively for the success of the project, under the careful supervision of the ASI. The success of the project has also been confirmed by the publication of several high quality scientific papers, [1-6].

The main goal of the project was to reconstruct high-resolution and well-focussed ISAR images of moving targets extracted from COSMO Skymed SAR images.

Spaceborne SAR has become a powerful tool for the Earth observation, by allowing wide areas to be monitored with low revisiting times. Such systems, such as COSMO SkyMed, originally employed in Earth observation applications, are also able to form high-resolution SAR images making them very attractive for both military and homeland security applications. In such applications, radar imaging of man-made non-cooperative targets (NCTRI) becomes one of the main interest as it can enable Automatic Target Classification (ATC).

Nevertheless SAR processors are based on the assumption that the illuminated area is static during the synthetic aperture formation. As a consequence of such an assumption, standard SAR techniques are unable to focus moving targets while forming a focussed image of the static scene. This leads to blurred and displaced images of any object that is not static during the synthetic aperture formation.

On the other end, ISAR techniques propose another way to look at the problem of forming well-focussed images of non-cooperative moving targets. ISAR techniques, in fact, do not rely on the assumption of stationary targets during the synthetic aperture formation, but instead they partly exploit the target's own motions to form the image.

Although ISAR techniques do not need any a priori information about the target's motions, some others constraints are required to form an ISAR image. Nevertheless ISAR imaging provides acceptable solutions when SAR fails, as it will be proven in this work.

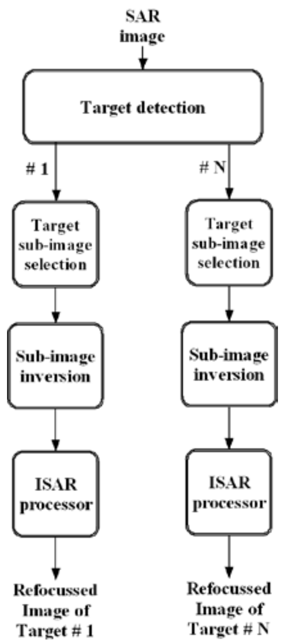


Figure 1: Block diagram of the overall system

Taking into account the advantages of COSMO

Proc. 'ESA Living Planet Symposium 2013', Edinburgh, UK
9–13 September 2013 (ESA SP-722, December 2013)

SkyMed system (wide areas monitoring, short revisit time, etc…), the problem was tackled starting from formed COSMO SkyMed SAR images.
The overall system concept is sketched in Fig. 1.
Although, this work focuses on spaceborne imaging of ship targets, it is worth mentioning that the overall concept could also be applied to ground and air moving targets [7-8] as well as to other radar platform, such as manned or unmanned airborne radar systems [4].
As it can be noticed by observing Fig. 1, the moving targets must be detected first. This is because ISAR techniques can process a target at a time. After that, a sub image containing the target of interest is cropped from the SAR image and transformed into a suitable data for the application of the ISAR technique. The ISAR processor then will provide a well-focussed image of the moving target in a fully spatial coordinate system.
The reminder of the paper is organised as follows. Section II deals with the detection technique. Section III describes both the "*target sub-image selection*" and "*sub-image inversion*". Section IV describes the ISAR processor. Finally, section V shows some real-data results.

2. SHIP TARGET DETECTION

The aim of this section is to describe the detection algorithm used to detect ship targets near coastal regions in the images produced by the COSMO Skymed system. The detection algorithm is composed of three main blocks, as shown in Fig. 2:

- A land masking stage that aims at removing land regions.
- A pre-screening stage that implements a pixel-by-pixel sliding detection rule to detect target's pixels.
- A discriminator stage that aims at clustering together pixels belonging to the same target.

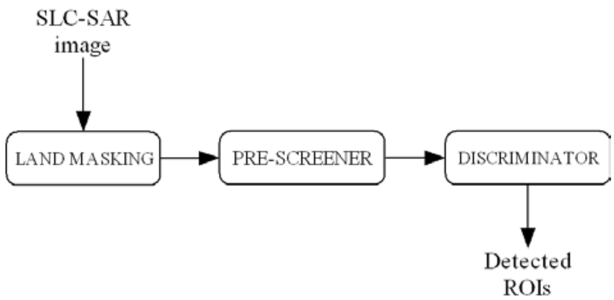


Figure 2: Block diagram of the ship detection technique

The pre-screener stage is implemented by means of a 2D CA-CFAR (Cell Average Constant False Alarm Rate). Specifically, the detector is based on the use of a two-dimensional sliding window centred on the Cell Under Test (CUT). An area of proper size containing only the sea clutter is then selected around the CUT. Since a target can occupy several resolution cells, to be sure that the background area is free of the target's pixels, a guard region of proper size is chosen around the CUT.
The intensity mean value computed on the background area is used to set the adaptive decision threshold. A target is detected when the CUT intensity is greater than the threshold. Details can be found in [6].
As already stated, the detector is followed by the discriminator. The discriminator aims at clustering together pixels belonging to the same targets. It allows the Region of Interest (ROI) containing the target to be extracted.
The discriminator is composed of 5 main steps:

- A "clean" morphological filter that removes isolated pixels;
- A labelling technique that identifies each group of detected pixels as a potential target via labelling procedure;
- A rejection step that discards groups of pixels that are not compatible with a ship or parts of it;
- A fusion step that via a proper merging technique avoids a single target to be split into multiple parts;
- A sidelobe removal step that removes clusters of detected pixels related to sidelobes of strong ground regions, which due to the high dynamic range between the coast and the sea regions cannot be deleted by conventional windowing functions;

As a final result, clusters of pixels are identified that could correspond to potential targets and that constitute the inputs of the following stages.

3. SUB-IMAGE SELECTION AND INVERSION

Once a target has been detected the target must be isolated. ISAR processors can in fact refocus a target at a time. SAR images are instead obtained by processing very large amount of data and could contain several targets, each with its own motions. Therefore, the same raw data used to form the SAR images cannot be used as input for the ISAR processor. The problem is then how to obtain an input data for the ISAR processor that can be considered as it was received in the presence of only a moving target. This problem can be solved by cutting a sub-image from the original SAR image, which contains only one target, and then back-projecting it back to the received data domain in order to obtain an equivalent raw data. Such equivalent raw data will then be used as input for the ISAR processor.
The target selection cannot be performed in the data domain, as the received signal is the sum of the signals backscattered from all the targets within the SAR scene. This operation can instead be performed in the image domain where the moving targets, even if unfocussed, have been detected and appear as separated ROIs.
The sub-image selection acts as a two-dimensional filter on the SAR image and it is essential because of the following reasons:

- More than one target may be detected in the SAR image.
- Noise and clutter are strongly attenuated as only the resolution cells occupied by the target are retained

whereas the rest is filtered out.

A data suitable for the application of the ISAR technique is then obtained by inverse Fourier transforming the sub-image containing the target of interest. Details can be found in [5].

A pictorial description of this technique is provided in Fig. 3.

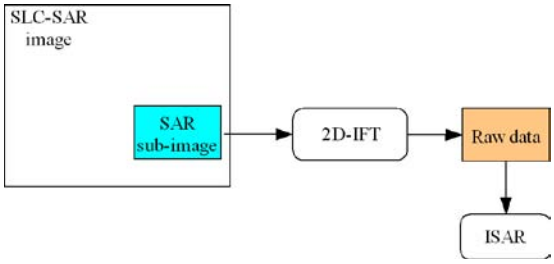


Figure 3: Block diagram of the data extraction technique

4. ISAR PROCESSING

The data obtained by inverse Fourier transforming the sub-image is then used to feed the ISAR processor, which provides a well-focussed image of the target. The ISAR processing adopted here makes use of the Image Contrast Based Autofocus (ICBA) algorithm, and a Fourier-based Range-Doppler technique for the image formation. ICBA is a parametric technique that aims at estimating the target's motion parameters by maximising the Image Contrast (IC) value. Details can be found in [9].

However, this technique relies on the assumption that the target's motions are smooth enough to generate a constant effective target's rotation vector during the processing time interval. The target's own motions may instead induce a non-uniform effective target's rotation vector. In order to minimise target's rotation variations, the Coherent Processing Interval (CPI) can be controlled via a time-windowing approach [10].

The ISAR technique then generates an image in the range-Doppler domain. In order to estimate the target size however an image in a fully spatial coordinate system is needed. The cross-range scaling algorithm [11] is then applied to the ISAR image in order to scale the Doppler axis from Hertz to meter.

A block scheme of the ISAR algorithm is depicted in Fig. 4 where the time-windowing block is represented with a dotted line, as it is not strictly necessary if the target's motions satisfy the requirement before mentioned.

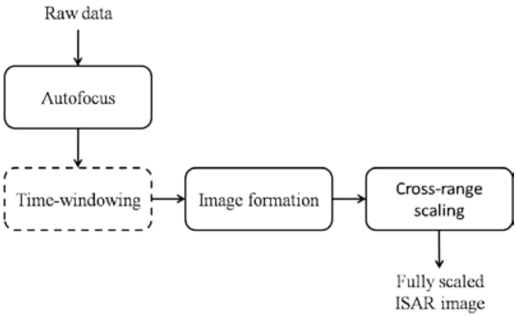


Figure 4: Block diagram of the ISAR technique

5. RESULTS

The aim of this section is to present the main results obtained by processing real COSMO Skymed spotlight SAR images by using the proposed algorithm. Specifically two experiments will be presented and the results of both the detection and the ISAR processing will be shown.

5.1. First experiment: archived COSMO SkyMed data

The first experiment has been carried out by using the COSMO Skymed SAR image record number 100501523. This SAR image has been acquired on April 23 2008 and covers the area of the Italian town Messina. The image is centred at 38.205006° N latitude and 15.557903° E longitude. The pixels spacing is 0.5828 m x 0.7016 m in slant-range and azimuth directions, respectively. The quick-look (QLK) image is shown in Fig. 5, while the corresponding optical image, from Google Earth Software, is shown in Fig. 6. Both the Messina's harbour and several ships are evident in the SAR image. Since no information about the ships is available, the detection performance will be evaluated through the comparison with the human visual interpretation of the same image.

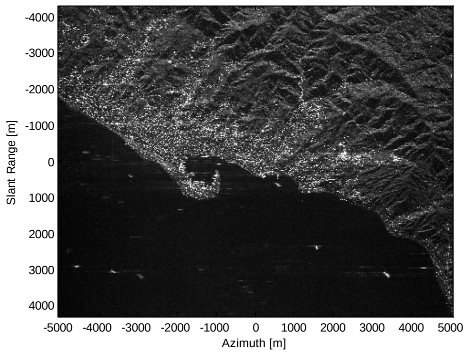


Figure 5: SLC COSMO Skymed SAR image that covers the area of Messina harbour

Figure 6: Satellite optical image of the same area of Fig. 5 (screenshot form Google Earth Software)

5.1.1. Detection results

In order to properly set the decision threshold, sub-images containing only sea pixels have been considered and processed by the ship detector described in Section 2.

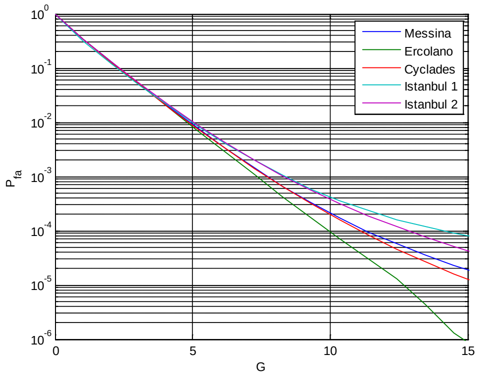


Figure 7: P_{fa} curve versus the gain G

As no targets are present in these sub-images, the Probability of False Alarm (P_{fa}) can be computed as the ratio between the number of detected pixels and the total amount of pixels in the sub-image. This leads to the graph in Fig. 7 where the P_{fa} is plotted against the gain parameter *G*.

In Fig. 7 the blue line represents the P_{fa} curve obtained by processing the SAR image covering the area of Messina. As it can be inferred by observing the same figure, others SAR images have been processed that cover different areas. However, only the results relative to the SAR image covering the area of Messina will be shown in this paper for the pages limitation. As expected, the P_{fa} is a decreasing function of the gain *G*, which represents the only parameter to be set in order to achieve a given P_{fa}.

Once the gain G has been set according to the desired P_{fa} (in this case $P_{fa} = 10^{-4}$), the 2D CA-CFAR has been applied to the SAR image. The result is shown in Fig. 8 where the red dots represent the pixels where the decision test exceeds the threshold.

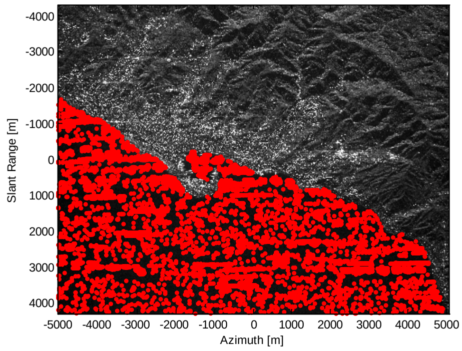


Figure 8: Output of the pre-screening stage

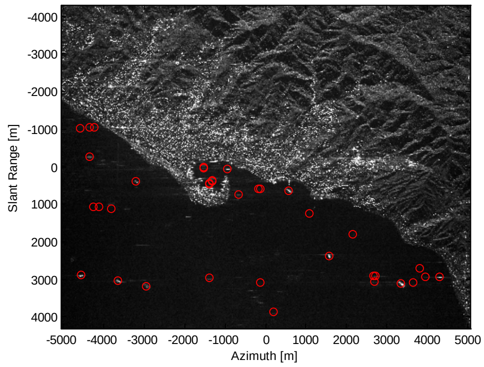


Figure 9: Final output of the discriminator

Fig. 8 shows a considerable number of detections.
The purpose of the discriminator step is to extract the ROIs around each potential target and to reject those detected pixels or group of pixels that correspond to false alarms.
The final output is given in Fig. 9 where the red circles represent the centroid of each ROI. The final number of candidate ships is 38. By means of a visual inspection only 7 ships seem to be present in the scene whereas 31 are false alarms.
Finally, the proposed ship detection algorithm is able to identify the regions occupied by the targets. These regions are the inputs of the following stages.

5.1.2. ISAR imaging results

A target has been chosen to test the ISAR processor performance. Specifically, the chosen target is highlighted in the red frame in Fig. 10.
Fig. 11 shows the ROI of the chosen unfocussed target whereas the well focussed ISAR image of the target is shown in Fig. 12. As it can be noted, any residual radial motions are removed after the application of the ISAR processing. The ISAR image has been obtained by exploiting the whole processing time interval as the target's motions satisfy the requirement needed for the application of the ISAR technique.

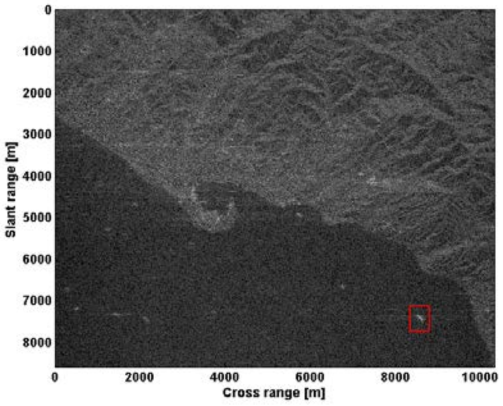


Figure 10: SAR image where the chosen target is highlighted with a red square

It should be noted that the ISAR image is represented in the classical hybrid Range-Doppler (RD) domain. In order to have an image in a fully spatial coordinate system, the cross-range scaling algorithm should be applied to the ISAR image. The fully scaled target image is shown in Fig. 13.

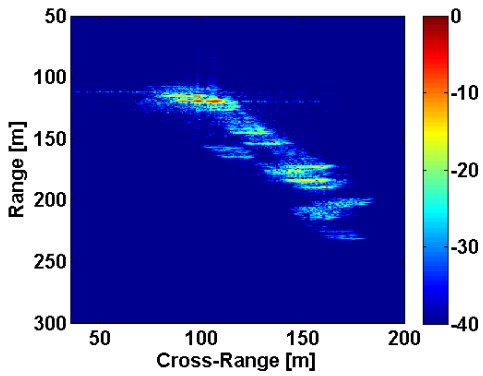


Figure 11: Sub-image of the target

It is worth noting that, although the actual length of the ship is unknown, the estimated length is a likely value. Moreover, it must be pointed out that the target is represented in the ISAR image plane, which does not necessarily coincide with the ground plane, therefore the target size can be underestimated.

The target appears much sharper and several individual scatterers are mapped into sinc-like shape Point Spread Function (PSF). Because of that, several target's features become clearly visible that may be used for classification and recognition purposes.

5.2. Second experiment: cooperative sailing ship

The aim of this experiment is two-fold:

- Demonstrate the COSMO Skymed capability to effectively image small and low Radar Cross Section (RCS) targets.
- Assess the performance of the proposed algorithm in terms of detection, image quality and estimated target's length, by exploiting a cooperative target.

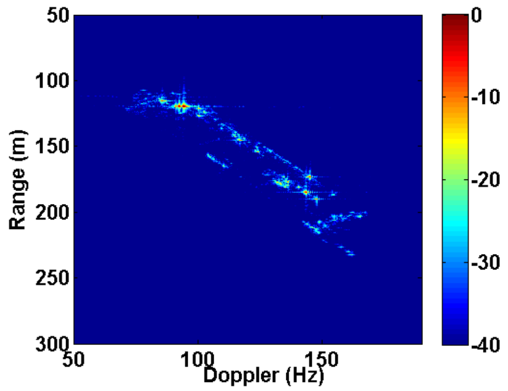


Figure 12: Well-focussed ISAR image of the target

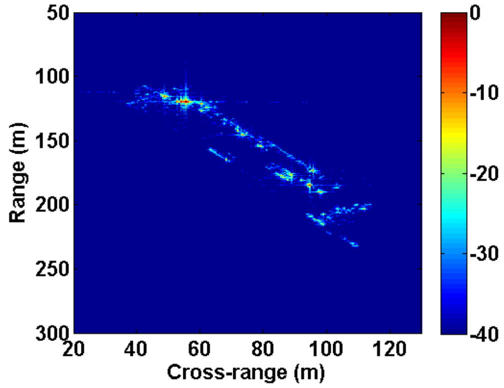


Figure 13: Well-focussed ISAR image of the target in a fully spatial coordinate system

The measurements were taken in False Bay, near Cape Town, South Africa in October 2010. The target was a cooperative small sailing ship. A picture of the target is shown in Fig. 14. The target was slowly sailing. Significant roll, pitch and yaw motions were induced by the sea waves. The target's position was continuously monitored by a GPS system during the acquisition time. Some of the most important COSMO Skymed system parameters are listed in Tab.1

Table 1: CSK system parameters

Transmitted bandwidth	220 MHz
Pulse Repetition Frequency	3041 Hz
Orbit	Ascending
Look	Left (Looking West)
Incidence angle	49°
Central frequency	9.6 GHz

A Google Earth image of the area is shown in Fig. 15, whereas a quickview of the SAR image obtained with the NEST Toolbox is shown in Fig. 16. In Fig. 16 the cooperative target is highlighted with a red square.

Figure 14: Picture of the cooperative target

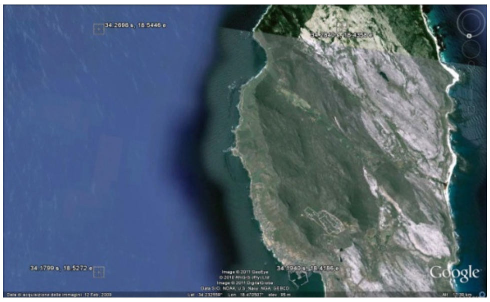


Figure 15: Google Earth image of the False Bay area

5.2.1. Detection results

As done previously, in order to properly set the decision threshold, a sub-image of an area free of targets is extracted from the SAR image. The obtained curve of the P_{fa} is shown in Fig. 17, where the theoretical curve refers to a normal distribution. Fig. 18 shows the processed sub-image that contains the cooperative target where the centroid of the target's ROI is represented with a red circle.

5.2.1. ISAR imaging results

The target's sub-image extracted by means of the detection algorithm is shown in Fig. 19, and it represents the input of the sub-image inversion step. After Fourier transforming the sub-image, the data is then provided in input to the ISAR algorithm.

As already stated the target experienced highly time variant motions due to the sea state. As a consequence the hypothesis of constant effective rotation vector does not hold in this experiment. In order to effectively apply the ISAR technique the integration time must be controlled by means of the time windowing algorithm. It must be pointed out that, because of the time dependence of the effective rotation vector the Image Projection Plane (IPP) may change from image to image. An ISAR image sequence is therefore obtained by windowing the data as shown in Fig. 20. Specifically, the images have been obtained by selecting a window of 0.8 sec with an overlapping of 0.4 sec. The effect of the ship's motions is evident as the image of the ship's master changes from positive to negative Doppler frequencies.

Finally, in order to have a fully scaled ISAR image, the cross range scaling has been applied to an ISAR image. The ISAR image in a fully spatial coordinate system is shown in Fig. 21.

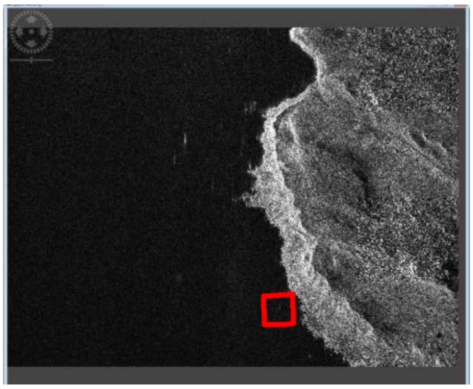


Figure 16: CSK SLC SAR image of the same area obtained by exploiting the NEST toolbox

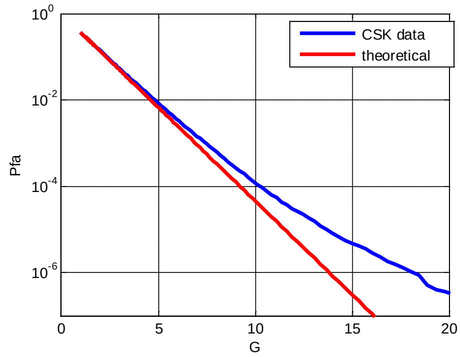


Figure 17: P_{fa} curve versus the gain G

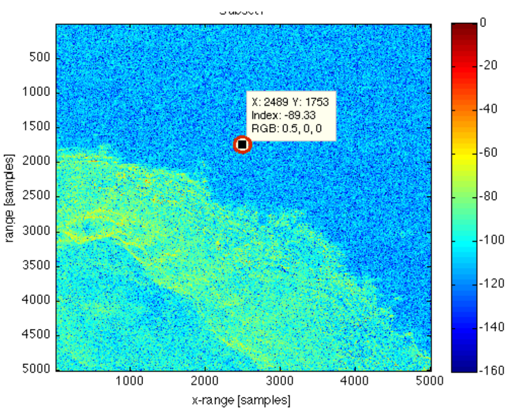


Figure 18: Final output of the detection algorithm

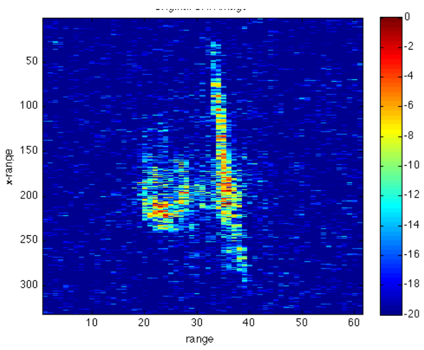
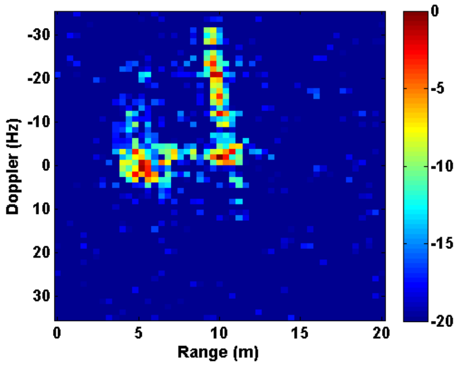
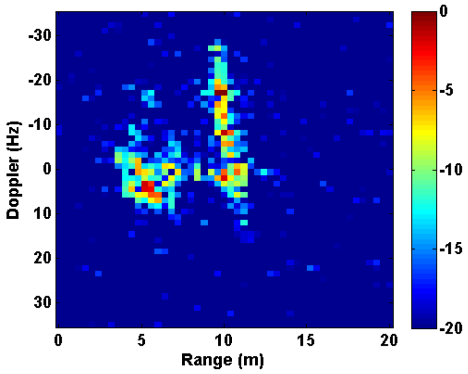


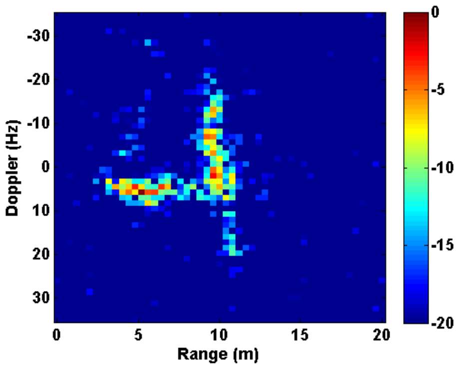
Figure 19: Sub-image containing the target. The axes are expressed as range and cross-range samples



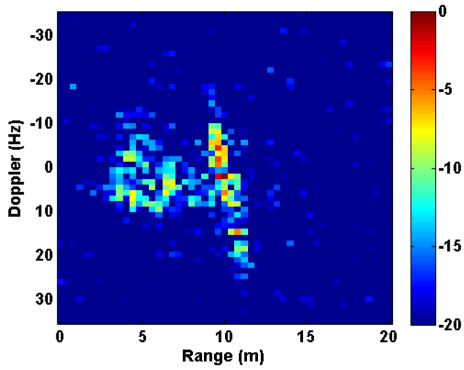
(a)



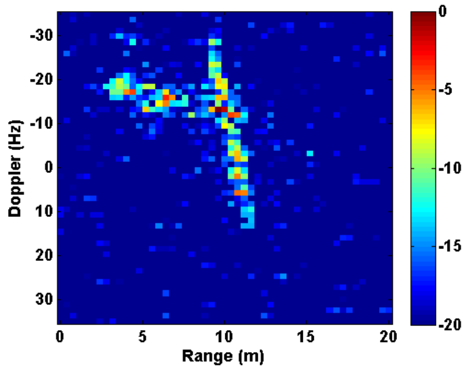
(b)



(c)



(d)



(e)

Figure 20: Sequence of 5 ISAR images

Before commenting the results few points must be highlighted:

- Parts of the ship are not visible in the ISAR image, specifically the stern. This can lead to an underestimation of the target length.
- The IPP is not a priori known and therefore the length of the ship's hull and mast could be underestimated from the ISAR image.
- Small targets usually provide a small number of strong reflectors. This usually affects the accuracy of the target's effective rotation vector estimator.

Tab. 2 shows the estimated ship length. The estimated length is smaller than the actual one, which can be explained by the reasons said before. However a good indication that the target's effective rotation vector is correctly estimated is given by the mast height estimation, which practically corresponds to the actual height.

Table 2: Estimated and actual ship size

	Length	**Mast height**
Actual size	13 m	12 m
Estimates	9.5 m	12.5 m

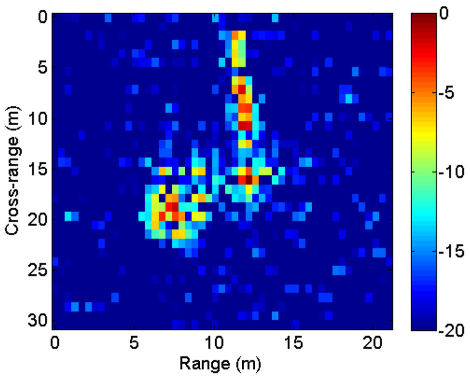


Figure 21: Fully scaled ISAR image of the target

6. CONCLUSIONS

A method to detect and focus moving targets in satellite high resolutions SAR images has been proposed. Examples obtained by processing COSMO Skymed spotlight SAR images have been shown. The analysis has highlighted that the proposed technique is able to automatically detect ship targets moving within the imaged SAR scene and to reconstruct well-focused ISAR images of the detected targets. These images can be usefully exploited for non-cooperative sea vessels classification and identification purposes, thus helping ATR (Automatic Target Recognition) procedures for maritime surveillance.

7. ACKNOWLEDGEMENT

The authors would like to thank the Italian Space Agency (ASI) for supporting and funding this project and for providing COSMO Skymed spotlight SAR images.

8. REFERENCES

1. Martorella, M., Berizzi, F., Pastina, D., Lombardo, P. (2011). Exploitation of Cosmo SkyMed SAR images for maritime traffic surveillance. *Radar Conference (RADAR), 2011 IEEE* , pp.113-117, 23-27 May 2011.

2. Martorella, M., Berizzi, F., Pastina, D., Lombardo, P. (2012). Maritime non-cooperative target imaging with COSMO SkyMed data. *Geoscience and Remote Sensing Symposium (IGARSS), 2012 IEEE International* , pp.3564-3567, 22-27 July 2012.

3. Martorella, M., Berizzi, F., Giusti, E., Bacci, A. (2011). Refocussing of moving targets in SAR images based on inversion mapping and ISAR processing. *Radar Conference (RADAR), 2011 IEEE* , pp.068,072, 23-27 May 2011.

4. Martorella, M., Giusti, E., Bacci, A., Berizzi, F., Meta, A. (2012). Non-cooperative maritime target imaging with an FMCW SAR system. *Synthetic Aperture Radar, 2012. EUSAR. 9th European Conference on* , pp.127,130, 23-26 April 2012.

5. Martorella, M., Giusti, E., Berizzi, F., Bacci, A., Dalle Mese, E. (2012). ISAR based techniques for refocusing non-cooperative targets in SAR images. *Radar, Sonar & Navigation, IET* , vol.6, no.5, pp.332,340, June 2012.

6. Pastina, D., Fico, F., Lombardo, P. (2011). Detection of ship targets in COSMO-SkyMed SAR images. *Radar Conference (RADAR), 2011 IEEE*, pp.928,933, 23-27 May 2011.

7. Pastina, D., Buratta, L., Turin, F. (2012). Detection of ground moving targets in COSMO-SkyMed SAR images. *Geoscience and Remote Sensing Symposium (IGARSS), 2012 IEEE International*, pp.3827,3830, 22-27 July 2012.

8. Pastina, D., Buratta, L., Turin, F., Cristallini, D. (2011). Exploiting COSMO-SkyMed spotlight SAR images for GMTI applications. *Radar (Radar), 2011 IEEE CIE International Conference on* , vol.2, no., pp.1918,1921, 24-27 Oct. 2011.

9. Martorella, M., Berizzi, F., Haywood, B. (2005). Contrast maximisation based technique for 2-D ISAR autofocusing. *Radar, Sonar and Navigation, IEE Proceedings*, vol.152, no.4, pp.253,262, 5 Aug. 2005.

10. Martorella, M., Berizzi, F. (2005). Time windowing for highly focused ISAR image reconstruction. *Aerospace and Electronic Systems, IEEE Transactions on* , vol.41, no.3, pp.992,1007, July 2005.

11. Martorella, M. (2008). Novel approach for ISAR image cross-range scaling. *Aerospace and Electronic Systems, IEEE Transactions on* , vol.44, no.1, pp.281,294, January 2008.