ADVANCED ISAR PROCESSING APPLIED TO VHR SAR DATA FOR SECURITY APPLICATIONS

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ABSTRACT

This work consolidates the existing results in the field of information extraction from spaceborne SAR imagery based on Inverse Synthetic Aperture Radar (ISAR) techniques, as well as enhances the understanding of the phenomenology, the models, the processing algorithms, the applications, and the overall value in security applications. The focus is on ISAR based advanced processing methods to explore the potentialities of very high resolution (VHR) SAR data in a range of security related application domains, including maritime, inland water, and land scenarios.

Index Terms— ISAR, TerraSAR-X, Capella Space, moving target image refocusing, motion parameters estimation.

1. INTRODUCTION

Nowadays, satellite-based synthetic aperture radar (SAR) systems are widely used in earth observation and are also a powerful tool for surveillance and security applications, providing moving target indication, recognition capabilities and motion parameters estimation. New generations of SAR systems can provide image products with fine spatial and higher temporal resolutions, better than 1-m, thanks to the combination of wide transmitted bandwidths and advanced operative modes based on very long dwells as well as revisiting multiple times in a day the same area. Constellations of commercial satellites (such as Capella and ICEYE) join to well-established institutional missions such as COSMO-SkyMed and TerraSAR-X, expanding the range of potentialities thanks to the availability of very high resolution, sharp and easily interpretable images with shorter revisit time.

Nevertheless, the SAR imaging mechanism, inherent in its design, introduces challenges when dealing with moving targets, causing them to appear defocused, shifted, and even disappearing completely, when standard focus processing, relying on scene stationarity, is applied [1]. Range velocity induces target shifts along the azimuth direction and smearing along the range, while range acceleration and azimuth velocity components introduce smearing and defocusing in different directions. The azimuth acceleration component further impacts the third-order phase, particularly observable in very high-resolution SAR data with extended aperture times. The cumulative impact of these defocusing effects reduces target contrast, leading to a low signal-to-clutter ratio in SAR intensity images, thereby adversely affecting target detection and recognition. Addressing these issues is critical for accurate target refocusing, motion parameter estimation, and, consequently, improved detectability, tracking, recognition, and activity detection.

Moving target identification (MTI) capabilities are generally achieved through the augmentation of SAR systems with multiple receive channels, leading to the increasing of system complexity and costs. Moreover, most of the available SAR satellite systems do not offer multiple receive channels. However, even single-receive-channel systems, prevalent in operational satellite SAR missions (e.g., Cosmo-SkyMed, CSG, TerraSAR-X, ICEYE, Capella Space, Umbra), can deliver satisfactory performance with suitable signal processing techniques ([2], [3]); this work focuses on this family of SAR systems.

In the framework of the project "Innovative SAR Processing Methodologies for Security Applications. Topic B1: Inverse SAR processing to enhance the capabilities to characterize targets/features of interest", funded by the European Space Agency (ESA), experimentation and development of algorithms are in progress for the correction of target defocusing effects resulting from unknown motion in both maritime and land scenarios. We leverage upon ISAR techniques, well-documented in the literature [5], which involve motion compensation and coherent integration processing to mitigate the effects of target motion and achieve accurate focusing.

This work aims at giving an overview on use cases of interest that can benefit of the integration of ISAR techniques in VHR spaceborne SAR data, including maritime, inland water, and land surveillance.

2. METHODS

The ISAR approaches adopted to achieve the project's aims include:

1) Parametric autofocus algorithms ([6], [7], [13]) based on the Chirp Scaling (CS) [8] technique, to remove efficiently defocusing effects due to range migration effects and azimuthal chirp rate mismatches.
2) Non-parametric autofocus algorithms based on the Phase Gradient Algorithm (PGA) ([9], [10]) able to remove defocusing terms, even higher than second order from the Doppler phase.
3) Azimuthal sub-aperture technique, to identify the larger sub-aperture in which the rotation velocity vector is constant and then cross-range scaling refocusing can be applied.
4) Cross-range scaling [11][12] refocusing, to remove defocusing effects due to rotation motion of the target under assumption that the rotation velocity vector is constant.

The exploitation of VHR data on different scenarios of interest, in addition to maritime ones, necessitates enhanced ISAR algorithms and workflows to improve accuracy in motion parameter estimation and refocusing to take into account different target types and background clutters and introducing moving target detection (sub- and over-clutter) algorithms.

3. APPLICATION AREAS AND PRELIMINARY EXPERIMENTAL RESULTS

To showcase the surveillance potentialities coming from VHR spaceborne SAR data, different use cases have been identified pertaining to different operative scenarios encompassing maritime, land and in-land water areas. For each one, the methods must be able to tackle different specific issues (e.g., different target-to-clutter contrast, lower for land applications and higher for maritime scenarios, or different target sizes, smaller for land applications and larger in maritime environment, etc.), and user needs.

Maritime domain awareness – to support an effective capability to monitor marine traffic in critical sea areas, neighboring of ports and, for fishery control, marine protected areas, as well as in open sea.

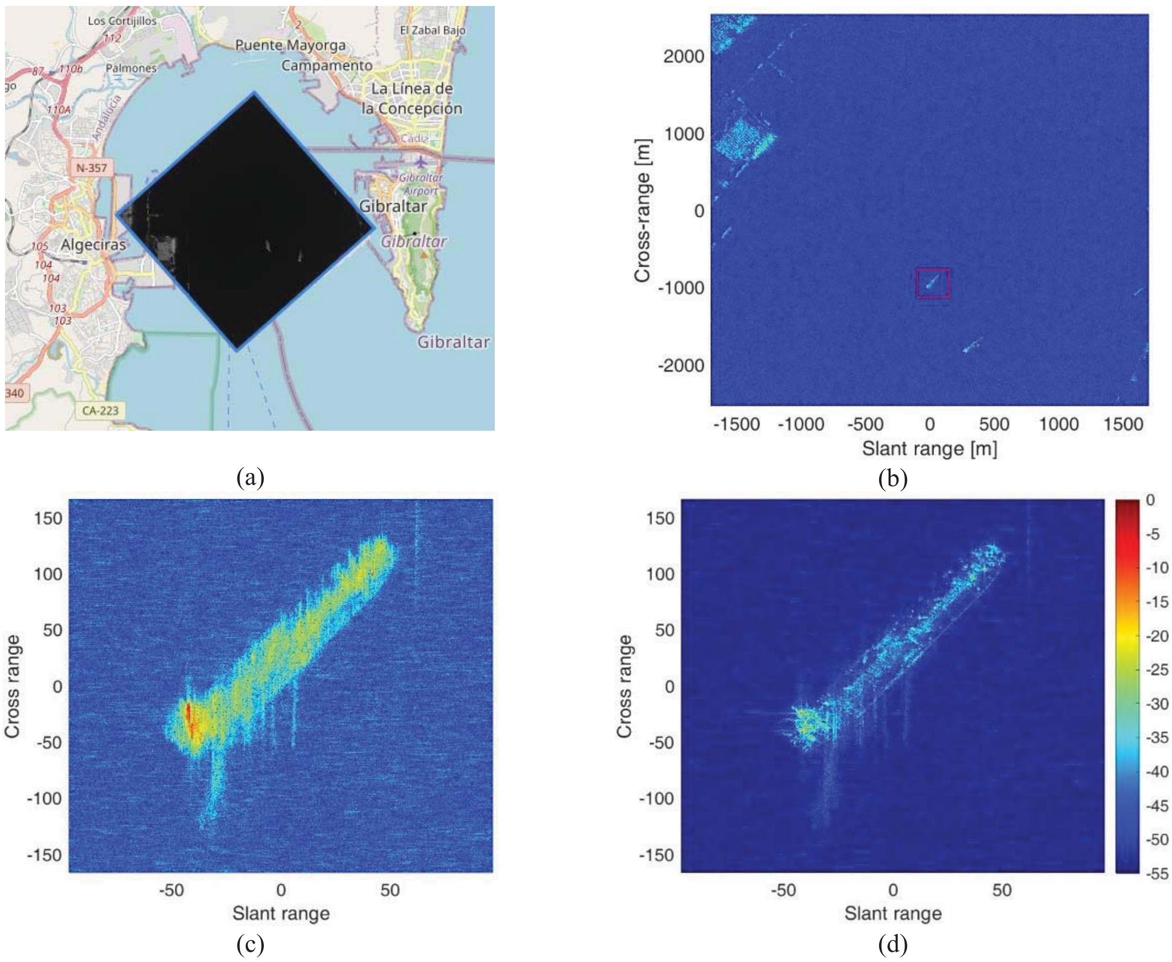

Figure 1 – Maritime domain scenario: (a) geographical area, (b) original Capella Space image, target in the red square, (c) original and (d) refocused sub-image.

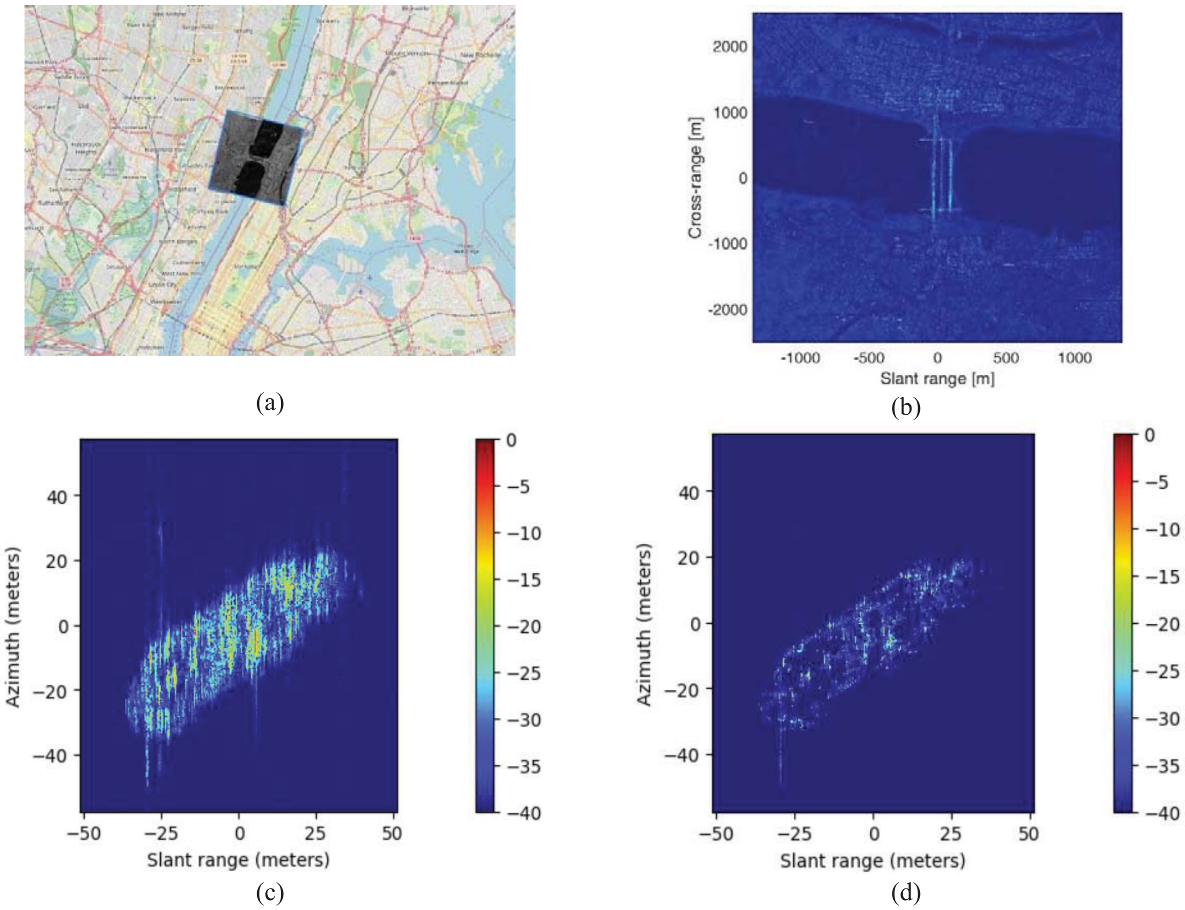

Figure 2 – In-land waterways scenario: (a) geographical area, (b) original Capella Space image, target (c) original and (d) refocused sub-image.

Here, an example concerning a littoral traffic scenario is provided using a Capella Space spotlight SAR image. Particularly, the image was acquired over the Strait of Gibraltar, 20/09/2021, 4:47:16 UTC covering an area of approximately 5 km × 5 km, with a very fine spatial resolution (slant range 0.27 m and cross range 0.44 m).

Figure 1a provides an overview of the observed area, showcasing the georeferenced SAR image, while Figure 1 b shows the original SLC SAR image. The target in the red frame is selected as opportunistic target to test the proposed approach. Figure 1c shows the original target sub-image, where the blurring along the cross-range direction due to target motion can be easily observed. The refocused image is provided in Figure 1d demonstrating a large quality enhancement. Moreover, from the translational motion compensation step, an azimuth velocity of approximately -2.25 m/s (around -4.92 kn) has been estimated.

In-land waterways surveillance – to monitor traffic on rivers, lakes, artificial waterways and large canals. Figure 2 shows results achieved pertaining a river crossing a densely populated area. The example focuses on the Hudson River crossing New York City (USA). The Capella Space SAR image (shown in Figure 2a superimposed to the geographical area) was acquired on January 22, 2021, at 22:54:06 UTC, in spotlight mode. This image covered an area of approximately 5 km × 5 km, with a very fine spatial resolution (range resolution of 0.27 m and azimuth resolution of 0.44 m). Original image and obtained products are shown in Figure 2b-d. The original SAR image of the moving vessels shows evident defocusing effects while instead the corresponding refocused image has very sharpened scattering features. Also in this case the azimuth velocity could be extracted from the estimated optimal Doppler rate in the refocusing process, while the range velocity by using azimuthal velocity and cruising direction. The range velocity is used to relocate the vessel in the exact position [14].

Land domain awareness – to support the surveillance of borders and of areas close to critical infrastructures (such as national borders, neighbors of critical infrastructures, illegal mining sites), for the identification of anomalous and/or illegal activities. An example of refocusing result for land targets in urban area (Rome, Italy) extracted from a

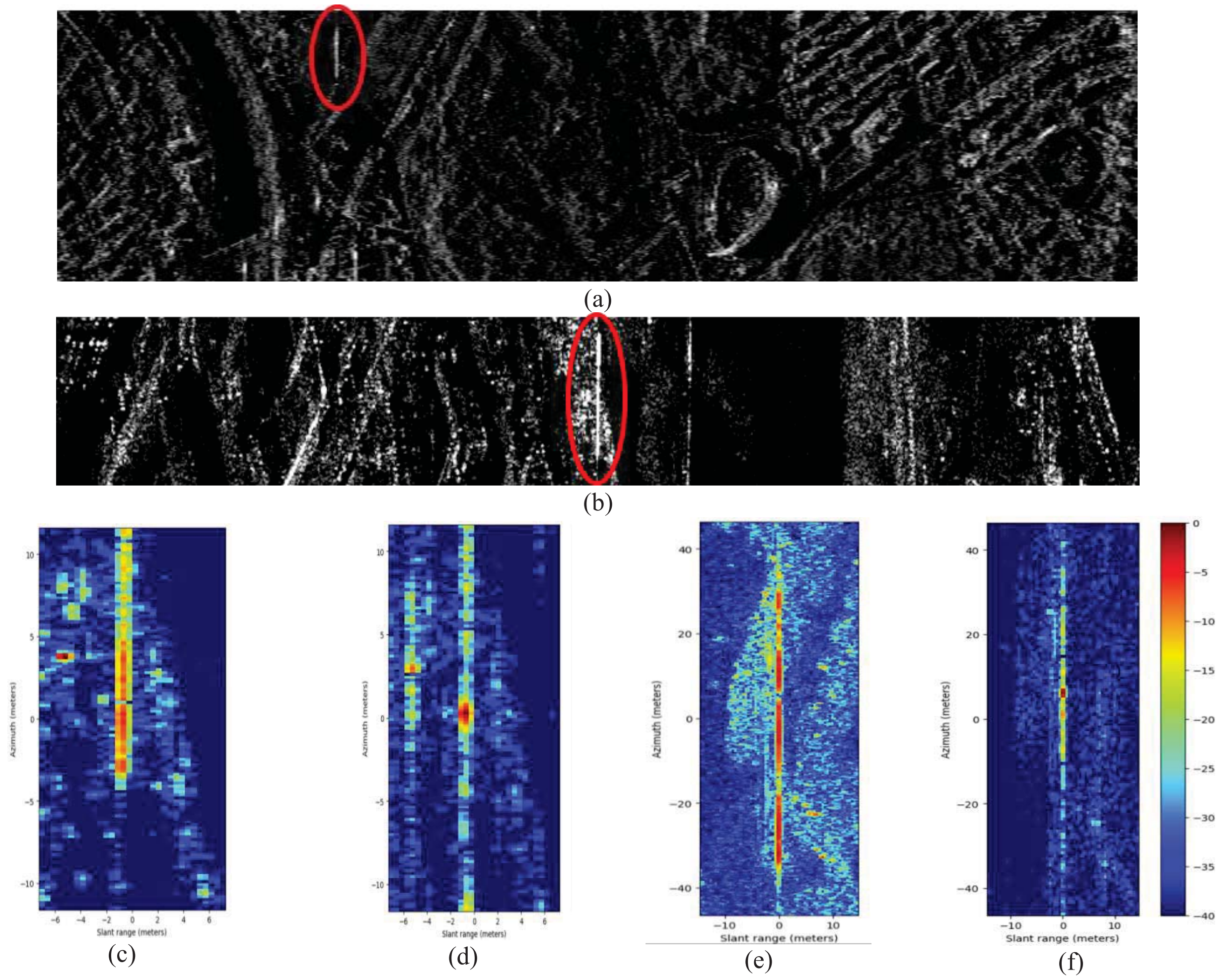

Figure 3 – Land scenario: original (a) first and (b) second sub-image from SLC TerraSAR image and (c)&(e) defocused and (d)&(f) refocused targets.

TerraSAR-X SAR data (30 April 2021), staring spotlight mode, is reported in Figure 3, with a range resolution of 0.6 m and an azimuth resolution of 0.24 m. Particularly, two opportunistic targets are here selected as examples and highlighted in the red ovals. Also in this challenging case the comparison between the original and refocused movers shows a significant improvement confirming the validity and suitability of the adopted processing solutions.

4. CONCLUSIONS

In the framework of the project "Innovative SAR Processing Methodologies for Security Applications. Topic B1: Inverse SAR processing to enhance the capabilities to characterize targets/features of interest." funded by the European Space Agency (ESA), we have developed ISAR based techniques to refocus SAR images of moving targets and estimate their motion parameters for a range of application domains.

The ISAR based processing chains are currently under experimentation on a large dataset of SAR data from VHR SAR systems, including TerraSAR-X and Capella Space satellites. The preliminary results here reported encourage the expansion of the net of potential users of VHR SAR missions from remote sensing to monitoring and surveillance applications, with the ultimate goal of operational use in future services.

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