Moving Target Focusing in SAR Image with Known Normalized Relative Speed

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***Abstract*—The paper presents the moving target focusing method which allows focusing moving targets in complex SAR images without raw data. The method is developed on the range migration algorithm where focusing moving target is an interpolation step in the wave domain. The simulated results are provided in the paper to illustrate the proposed method whereas the experimental results show its practicality. The method can be flexibly applied from small area to the whole SAR scene.**

***Index Terms*—SAR, ground moving target, focusing, Range Migration, Stolt interpolation, UWB.**

I. Introduction

Ground Moving Target Indication (GMTI) is considered to be one of the most important applications of Synthetic Aperture Radar (SAR). In comparison to other GMTI solutions, SAR GMTI has the advantage in imaging capability. In other words, SAR GMTI allows us to obtain the image of the detected target and this capability is unavailable for other GMTI solutions. An image of a target is usually very important for surveillance or reconnaissance. It is common knowledge that a moving target is displaced and blurred in a SAR image and the signature in that SAR image is usually an elliptical or hyperbolic curve. A summary of the solutions to refocus moving targets in SAR images is given in [1]. Basically, the solutions can be divided into two groups: estimation of target motion parameters and combination of data reformatting with high order Doppler history analysis. One example of the former group is found in [2] where the estimates of unknown target motion parameters are based on three prominent points in the image of the target. These estimates are bases for phase compensation and data formatting in order to eliminate motion-induced phase errors. A typical solution of the later group is known as Keystone transform [3]. The method simultaneously eliminates the effects of linear range migration for all moving targets regardless of their unknown velocity using a one-dimensional interpolation of the deramped phase history. Other versions of Keystone can also be found in recent publications like [4]. Generally, the solutions work well with the data of conventional SAR systems where the signature of a moving target is usually contained in a single range cell.

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For UWB SAR systems, the methods for conventional SAR like Keystone are insufficient as the approximations are generally invalid. In addition, the signature of a moving target illuminated by a UWB SAR system can occupy several range cells that would be a challenge for the phase correction even if the approximations in Keystone were available for UWB SAR. Some solutions developed for focusing moving target in UWB SAR have been introduced recently. For example in [5], scaling the speed of SAR platform with normalized relative speed in range calculation is suggested for time domain algorithms. This method has been shown to focus moving targets in a SAR image correctly but the method also blur other stationary targets and objects which sometimes is undesired. Thank for the local processing characteristics of the time domain algorithms, we can minimize the focusing effects to stationary targets and objects by processing separately an area where a moving target is present. Scaling the speed of the platform with normalized relative speed to focus the moving target is also applied to the frequency domain algorithms such as Chirp Scaling [5] or Range Migration [6]. The methods basically require raw data. Other types of data like complex SAR image in the matrix form are not available for such methods. It is worth to mention that moving target focusing can be a basis for GMTI methods but can be a separate approach after GMTI.

The idea on focusing moving target without raw data is briefly sketched in [7] where moving target relative speed estimate is the main topic. According to [7], the area of interest (or subimage), where a ground moving target is present, is first extracted from the complex SAR image. The detected moving target is then focused using normalized relative speed and the range migration approach. The area of interest with focused moving target is finally inserted back to the SAR image. The procedure to focus moving target is repeated until the target is fully focused. A simulated ground moving target has been used to illustrate the proposal. A similar approach is introduced recently in [8], [9] where the data has been adaptively refocused using the matched filter bank approach jointly with Range Doppler.

In this paper, we concentrate on the derivation of the focusing method in connection with the Range Migration algorithm. The experimental results are based on the complex CARABAS image under the assumption that the target has been detected and the knowledge of normalized relative speed. This assumption comes from the reality that the detection and estimation have been performed [5].

The rest of the paper is organized as follows. Section

II reviews the Range Migration algorithm and the method for moving target focusing on raw data, i.e., before image formation. The derivation of the method for moving target focusing on complex SAR image, i.e., after image formation is presented in Section III. Several simulation results are presented in Section IV to illustrate the proposal, to compare it to the the original approach, and to show the advantages of the proposal. Section V is reserved for the experimental results based on the available CARABAS' data. The conclusions are summarized in Section VI.

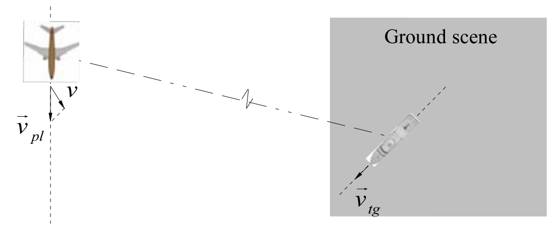

Fig. 1. SAR scenario with a SAR system illuminating a ground scene where a moving target is present.

II. Range Migration and Moving Target Focusing before Image Formation

In this section, we briefly present the range migration algorithm and a method to focus moving target in a complex SAR image with know normalized relation speed.

A. Range migration

Range Migration [10] is known as a frequency domain algorithm which allow forming SAR images of a large ground scene with high resolution. The processing steps of the algorithm include 2-D Fourier transform, Stolt interpolation and 2-D inverse Fourier transform. In the first step, the raw data in time-domain is transformed to frequency domain by 2-D Fourier transform

$$S\left(k_x, \rho=0, \omega\right) = \iint s\left(x, \rho=0, t\right) \mathrm{e}^{-j\left(k_x x+\omega t\right)} dx\ dt \quad (1)$$

where x and ρ are cross-range or azimuth and range, respectively, t is range time and $s\left(x, \rho=0, t\right)$ is a complex function representing the radar echoes. This complex function can also be written as the 2-D inverse Fourier transform of $S\left(k_x, \rho=0, \omega\right)$ as

$$s\left(x, \rho=0, t\right) = \iint S\left(k_x, \rho=0, \omega\right) \mathrm{e}^{j\left(k_x x+\omega t\right)} dk_x\ d\omega \quad (2)$$

It can be shown that a wave-field at ρ is expressed by

$$S\left(k_x, \rho, \omega\right) = S\left(k_x, \rho=0, \omega\right) \mathrm{e}^{j k_\rho \rho} \quad (3)$$

where the wavenumbers k_x, k_ρ and the angular frequency ω are linked together by the relationship

$$\omega = \frac{\mathrm{c}}{2}\sqrt{k_x^2+k_\rho^2} \quad (4)$$

In the next processing step, the variable ω is changed to the variable k_ρ using the relationship (4)

$$S\left(k_x, \rho, \omega\right) \longmapsto S\left(k_x, \rho, \frac{\mathrm{c}}{2}\sqrt{k_x^2+k_\rho^2}\right) = S\left(k_x, \rho=0, \frac{\mathrm{c}}{2}\sqrt{k_x^2+k_\rho^2}\right) \mathrm{e}^{j k_\rho \rho} \quad (5)$$

The change of variable is one of the main processing steps of Range Migration involving the so called Stolt interpolation.

In the last step, a 2-D inverse Fourier transform of (5) back to the time-domain at the time $-t_0$, when the collection of data starts, is carried out. The 2-D inverse Fourier transform results in

$$s\left(x, \rho, t=-t_0\right) = \iint \left(\frac{\mathrm{c}}{2}\frac{k_\rho}{\sqrt{k_x^2+k_\rho^2}}\right) S\left(k_x, \rho=0, \frac{\mathrm{c}}{2}\sqrt{k_x^2+k_\rho^2}\right) \mathrm{e}^{-j\frac{\mathrm{c}t_0}{2}\sqrt{k_x^2+k_\rho^2}} \mathrm{e}^{j\left(k_x x+k_\rho \rho\right)} dk_x\ dk_\rho \quad (6)$$

B. Moving target focusing in a complex SAR image

Let's consider a simple SAR scenario with a SAR system illuminating a ground scene where a moving target is present as illustrated in Fig. 1. The platform's velocity and the target's velocity are denoted by $\vec{v}_{pl}$ and $\vec{v}_{tg}$, respectively. If the SAR platform moves with a velocity that is defined by

$$\vec{v} = \vec{v}_{pl} - \vec{v}_{tg} \quad (7)$$

then the target is relatively stationary with respect to the SAR platform. The velocity given by (7) is known as relative velocity. This principle can be used to focus moving targets in complex SAR images. As proposed in [6], a moving target can be focused by modifying the relationship (4)

$$\omega = \frac{\mathrm{c}}{2}\sqrt{\left(\frac{k_x}{\gamma}\right)^2+k_\rho^2} \quad (8)$$

where γ is the normalized relative speed (NRS) and defined by

$$\gamma = \left|\frac{\vec{v}}{\vec{v}_{pl}}\right| \quad (9)$$

For a stationary target, $\vec{v}_{tg} = \vec{0}$ or $\gamma = 1$. We can see that the modification of (4) is nothing else than scaling the speed of the SAR platform with a factor of γ. The complex SAR image with moving target focusing is therefore presented by

$$\tilde{s}\left(x, \rho, t=-t_0\right) = \iint \left(\frac{\mathrm{c}}{2}\frac{k_\rho}{\sqrt{\frac{k_x^2}{\gamma^2}+k_\rho^2}}\right) S\left(\frac{k_x}{\gamma}, \rho=0, \frac{\mathrm{c}}{2}\sqrt{\frac{k_x^2}{\gamma^2}+k_\rho^2}\right) \mathrm{e}^{-j\frac{\mathrm{c}t_0}{2}\sqrt{\frac{k_x^2}{\gamma^2}+k_\rho^2}} \mathrm{e}^{j\left(k_x x+k_\rho \rho\right)} dk_x\ dk_\rho \quad (10)$$

III. Range Migration and Moving Target Focusing after Image Formation

In many cases, the raw data is unavailable so that the approach presented in the previous section to focus moving targets cannot be used. Even if the raw data is available, using the approach presented in the previous section results in a SAR image with a refocused moving target while other targets both stationary and moving are smeared. A method that locally focus a moving target without affecting others is therefore desired.

Let's take an example that a complex SAR image has been formed with the raw data and the moving target appears in that SAR image as an elliptical or hyperbolic curve [5]. We assume that there is no loss in unambiguous spectral information of fast moving targets. Hence, the complex SAR image used for this method must be correctly sampled otherwise the targets cannot be properly refocused. The true normalized relative speed is γ. The question is how to refocus the moving target in the SAR image without raw data. We start with a SAR image presented by (6). A 2-D Fourier transform of (6) gives us the terms inside the integral (6)

$$\mathcal{F}\left[s\left(x,\rho,t=-t_0\right)\right]= \frac{\mathrm{c}}{2}\frac{k_\rho}{\sqrt{k_x^2+k_\rho^2}}S\left(k_x,\rho=0,\frac{\mathrm{c}}{2}\sqrt{k_x^2+k_\rho^2}\right)\mathrm{e}^{-j\frac{ct_0}{2}\sqrt{k_x^2+k_\rho^2}} \tag{11}$$

The complex terms are then removed by multiplying with the associated conjugate complex terms as well as the inversion of quotient

$$\frac{2}{\mathrm{c}}\frac{\sqrt{k_x^2+k_\rho^2}}{k_\rho}\mathcal{F}\left[s\left(x,\rho,t=-t_0\right)\right]\mathrm{e}^{j\frac{ct_0}{2}\sqrt{k_x^2+k_\rho^2}} = S\left(k_x,\rho=0,\frac{\mathrm{c}}{2}\sqrt{k_x^2+k_\rho^2}\right) \tag{12}$$

To focus the moving target, the interpolation is necessary to based on (8) instead of (4). Please note that for each value of ω, (4) and (8) will result into different values of k_ρ. If we call $k_{\rho,1}$ and $k_{\rho,2}$ the values given by (4) and (8), respectively, the relationship between $k_{\rho,1}$ and $k_{\rho,2}$ are derived by equalize (4) and (8) as

$$\begin{aligned}\frac{\mathrm{c}}{2}\sqrt{k_x^2+k_{\rho,1}^2} &= \frac{\mathrm{c}}{2}\sqrt{\left(\frac{k_x}{\gamma}\right)^2+k_{\rho,2}^2}\\ k_x^2+k_{\rho,1}^2 &= \left(\frac{k_x}{\gamma}\right)^2+k_{\rho,2}^2\\ k_{\rho,1} &= \sqrt{\left(\frac{1}{\gamma^2}-1\right)k_x^2+k_{\rho,2}^2}\end{aligned} \tag{13}$$

Moving target focusing is here equivalent to a change of variable from $k_{\rho,1}$ to $k_{\rho,2}$ based on the relationship (13) as

$$S\left(k_x,\rho=0,\frac{\mathrm{c}}{2}\sqrt{k_x^2+k_{\rho,1}^2}\right)\longmapsto S\left(\frac{k_x}{\gamma},\rho=0,\frac{\mathrm{c}}{2}\sqrt{\left(\frac{k_x}{\gamma}\right)^2+k_{\rho,2}^2}\right) \tag{14}$$

TABLE I
Parameters of CARABAS.

Parameter	Values
Frequency range	20−90 MHz
Pulse duration	5 μs
Platform speed	130 m/s
Aperture step	0.9375 m
PRF	138 Hz
Flight altitude	3700 m
Minimum range	4600 m
Considered integration time	20 s

After this interpolation step, the interpolated data is multiplied with the scale factor and exponential function given by k_x/γ. A 2-D inverse Fourier transform will give us a SAR image with the focused moving target of interest

$$\tilde{s}\left(x,\rho,t=-t_0\right)= \mathcal{F}^{-1}\left[\frac{\mathrm{c}k_\rho\mathrm{e}^{-j\frac{ct_0}{2}\sqrt{\frac{k_x^2}{\gamma^2}+k_\rho^2}}}{2\sqrt{\frac{k_x^2}{\gamma^2}+k_\rho^2}}S\left(\frac{k_x}{\gamma},\rho=0,\frac{\mathrm{c}}{2}\sqrt{\frac{k_x^2}{\gamma^2}+k_\rho^2}\right)\right] \tag{15}$$

In summary, moving target focusing after image formation is implemented in the following sequence:

- Selection of area of interest in complex SAR image
- 2-D Fourier transform of area of interest
- Removal of exponential terms and rescaling of data according to (12)
- Change of variables from $k_{\rho,1}$ to $k_{\rho,2}$ according to (14)
- Rescaling data after interpolation and insertion of required exponential terms according to (15)
- 2-D inverse Fourier transform of the rescaled complex data.

IV. Simulation results

In this section, we present some simulation results on moving target focusing to review the original approach presented in section II.A and examine the proposal presented in section III. This allows us to compare the performance of the approaches. We simulate here an airborne UWB SAR system with long integration time and the ground scene with the presence of both stationary and moving targets.

A. Simulated SAR system and ground scene

The parameters for the SAR system simulation come from CARABAS [11], an airborne UWB SAR system of Sweden. Table I summarizes the main parameters that have been used in a measurement campaign in Sweden. What should be noted from Table I is only that, we consider a much shorter aperture in comparison to the real aperture in the simulations for illustration purposes.

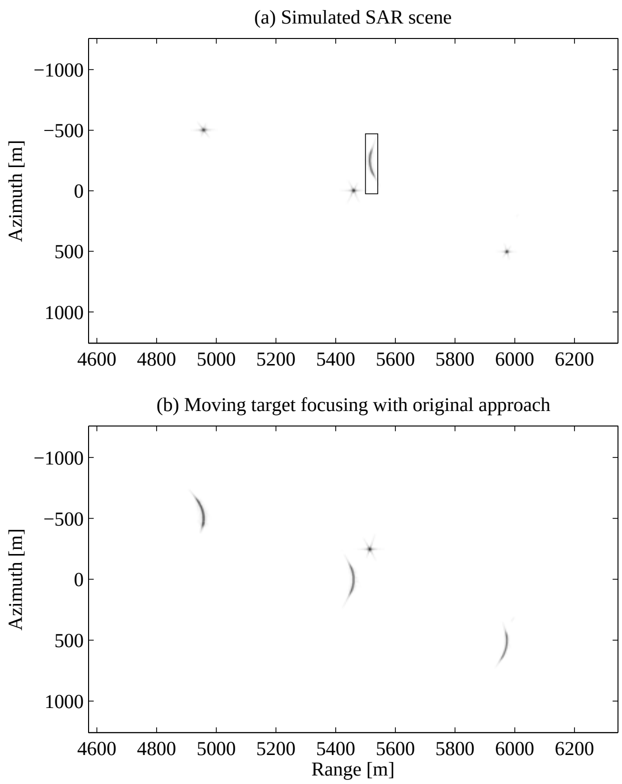

Fig. 2. (a) SAR images of the simulated ground scene, (b) Moving target focusing with the original approach.

The ground scene is simulated by three stationary targets and one moving target. The simulated targets are point-like scatterers and have the same radar cross section. The speed of the moving target vehicle is 30 km/h and the direction of movement is 45^o with respect to the flight direction. According to (9), this arrangement gives us a normalized relative speed of $\gamma = 0.9553$.

Figure 2(a) shows the whole SAR image of the simulated ground scene. Please note that the wave number k_x of the range migration algorithm is defined by

$$k_x = \frac{2\pi f_a}{v_{pl}} \tag{16}$$

where f_a denotes the azimuth frequency and takes the values in the range $[-\mathrm{PRF}/2\ \mathrm{PRF}/2]$.

As observed, three stationary targets are well focused and appear as the point-like scatterers whereas the moving target is blurred as a hyperbolic curve in the SAR image.

B. Focusing with the original approach

With the available raw data, we can easily focus the moving target by using the relationship (8). Hence, the raw data is first transformed to the frequency domain by a 2-D Fourier transform. The wave number k_x is now defined by

$$k_x = \frac{2\pi f_a}{\gamma v_{pl}} \tag{17}$$

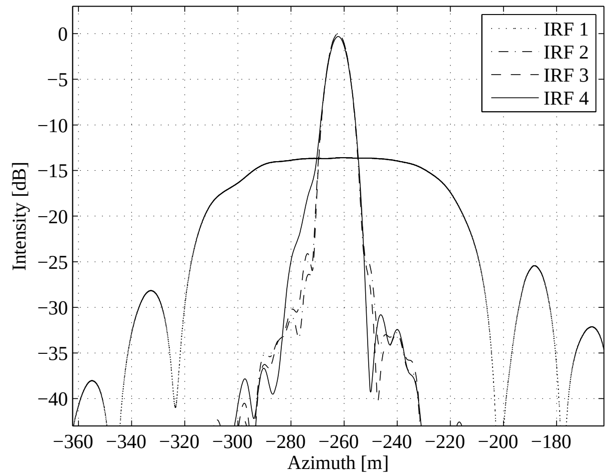

Fig. 3. Normalized azimuth vectors extracted from Fig. 2(a), Fig. 2(b), Fig. 4(a) and Fig. 4(b). The extracted vectors are associated with the peak intensity of the moving target focused in the SAR images as point-like scatterers and extracted in azimuth direction.

where $\gamma = 0.9553$ in this case. The change of variable from ω to k_ρ relies on the relationship (8). The data after the interpolation is scaled with the factor and multiplied with the exponential term given in (10). A 2-D inverse Fourier transform of the obtained data will result into a SAR image with the focused moving target.

The SAR image with moving target focusing is provided in Figure 2(b). As shown, the moving target is now correctly focused and appears in the SAR image as a point-like scatterer. However, the whole SAR image is updated with this focusing approach. Namely, the stationary targets are now blurred and appear as elliptical curves. However, blurring the small area surrounding the moving target is better than blurring whole SAR image. This allows observing both the focused moving target and whole SAR scene.

To get an analytical view of the focusing effects, we extract an vector from Fig. 2(b) and plot them in Fig. 3. The extracted vector is associated with the peak intensity of the moving target focused in the SAR image as a point-like scatterer and extracted in azimuth direction. In Fig. 3, it is denoted by IRF 2 where IRF is the abbreviation of Impulse Response Function. The same coordinates used to extract another azimuth vector from Fig. 2(a). This azimuth vector is also plotted in Fig. 3 and denoted by IRF 1. For convenience, the azimuth vectors are normalized with respect to the peak intensity of IRF 2.

As observed from Fig. 3, with the focusing, the gain in intensity is about 13.5 dB while the gain in azimuth resolution (given by the half power beamwidth) is about 8 times (60.2 m for IRF 1 and 7.4 m for IRF 2).

C. Focusing whole SAR image with the new approach

It is now assumed that the raw data is unavailable and moving target focusing is desired. First, we transform the complex SAR image given in Fig. 2(a) to the wave number domain by a 2-D inverse Fourier transform. We remove the scale factor and the exponential term in (11) by dividing the

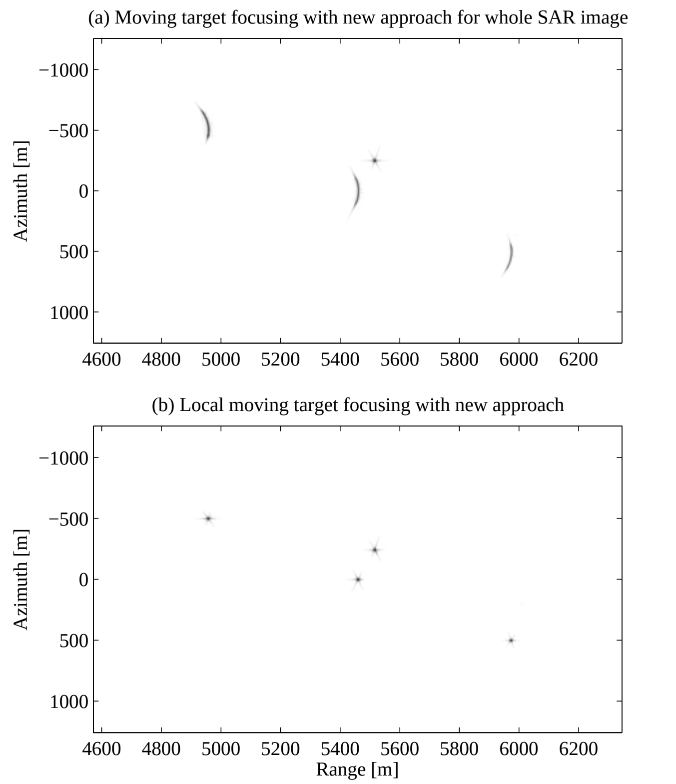

Fig. 4. (a) Moving target focusing with the original approach for whole SAR image, (b) Local moving target focusing with the new approach.

complex data with the same factor and multiplying the data with its conjugate complex as shown in (12).

The wave number k_x is now defined again by (17) instead of (16). The change of variable from $k_{\rho,1}$ to $k_{\rho,2}$ is based on the relationship (13). Then, the data after interpolation is scaled with the factor and multiplied with the exponential term that can be found from both (10) and (15). Finally, the SAR image with moving target focusing will achieved by a 2-D inverse Fourier transform of the obtained data.

Figure 4(a) shows the SAR image with moving target focusing using the new approach without the raw data. The performance of the approach is very similar to the original one. We can focus the moving target correctly but defocuse the stationary target at the same time. The azimuth vector extracted from Fig. 4(a) is plotted in Fig. 3 for analytical performance evaluation and denoted by IRF 3. The same gains in intensity (13.5 dB) and azimuth resolution (8 times) are obtained with the new approach.

As mentioned, the defocusing effect to the stationary target is sometimes not desired. To avoid this, we can use the new approach for local focusing as presented in the next subsection.

D. Local focusing with the new approach

It is now assumed that the raw data is unavailable and moving target focusing is desired. However, the effect of the focusing approach is expected to be minimized. In other words, the focusing approach will focus only the moving target of interest without affecting the others. To do this, we can select a small area surrounding the target, e.g. the rectangular area 562.5 m×73.0 m marked by the black rectangle in Fig. 2(a) and process this area separately using the new approach. The processing steps are similar to the previous subsection. The extracted area with moving target focusing is then inserted back to the extracted part of the SAR image.

Figure 4(b) shows the SAR image with local moving target focusing using the new approach without the raw data. It is obvious that we can focus the moving target correctly but the processing does not affect the other parts of the SAR image. The stationary targets are still well focused. The azimuth vector is extracted from Fig. 4(b) and also plotted in Fig. 3 for evaluation. The azimuth vector is denoted by IRF 4. The same azimuth resolution (8 times) but a slightly lower gain in intensity (13 dB) are obtained with the local focusing using the new approach. This slight difference comes from the fact that there is a stationary target that is close to the moving target.

However, the gain in processing time is significant when compared to processing the whole SAR image. If we look at the processing sequence presented in Section III, the complexity of the new approach comes from the 2-D Fourier transform of area of interest ($MN\log_2[MN]$), the change of variables from $k_{\rho,1}$ to $k_{\rho,2}$ (depending on the interpolation method but $\propto MN$), and the 2-D inverse Fourier transform of the rescaled complex data ($MN\log_2[MN]$). The complexity is hence proportional to the area of interest (MN). For local focusing, the area of interest, in this example, is smaller than the whole SAR image 108 times. In other words, the processing time is reduced by a factor of 108.

V. Experimental results

In this section, we present the experimental results on raw data to examine the local moving target focusing approach. We used CARABAS data collected in the area of Simrishamn, located along the Baltic coastline in southern Sweden. The parameters for the registration are given in Table I and have also been used to generate the simulated data in the previous section. Here we consider the complete aperture of 20480 positions and the corresponding integration time is about 150 s, i.e. 7.5 times the one used in the simulations. The complex SAR image of the ground scene is formed with the backprojection algorithm and provided in Fig. 5(a). The area surrounding an elliptical curve visible in the middle left of the SAR image, where the presence of a moving target has been detected. The normalized relative speed is $\gamma = 0.96$ [5]. The zoom-in of the area of interest is provided in Fig. 5(b).

The small area surrounding the elliptical curve 600 m×60 m is selected and extracted from the complex SAR image. This extracted area is processed in the similar way presented in the previous subsections. The extracted area with moving target focusing is then inserted back to the extracted part of the SAR image.

Figures 6(a) and 6(b) show the SAR scene with local moving target focusing and the zoom-in of the area of interest with the focused moving target, respectively. Here we can also

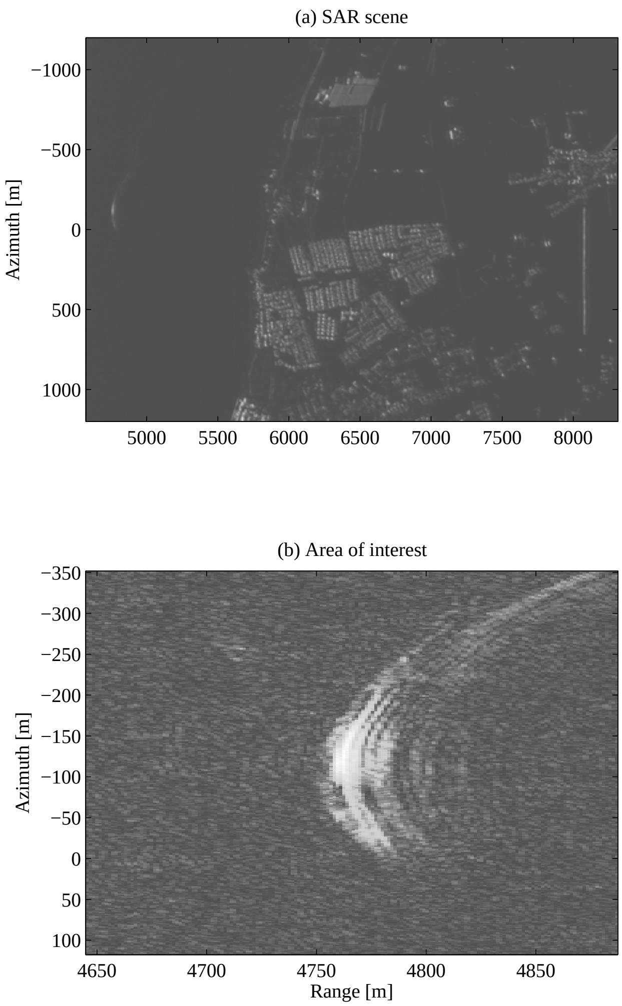

Fig. 5. Ground scene in the area of Simrishamn, located along the Baltic coastline in southern Sweden, is imaged by CARABAS with parameters given in Table I. The area surrounding a hyperbolic curve visible in a SAR image, where the presence of a moving target has been detected. (a) SAR scene. (b) Area of interest.

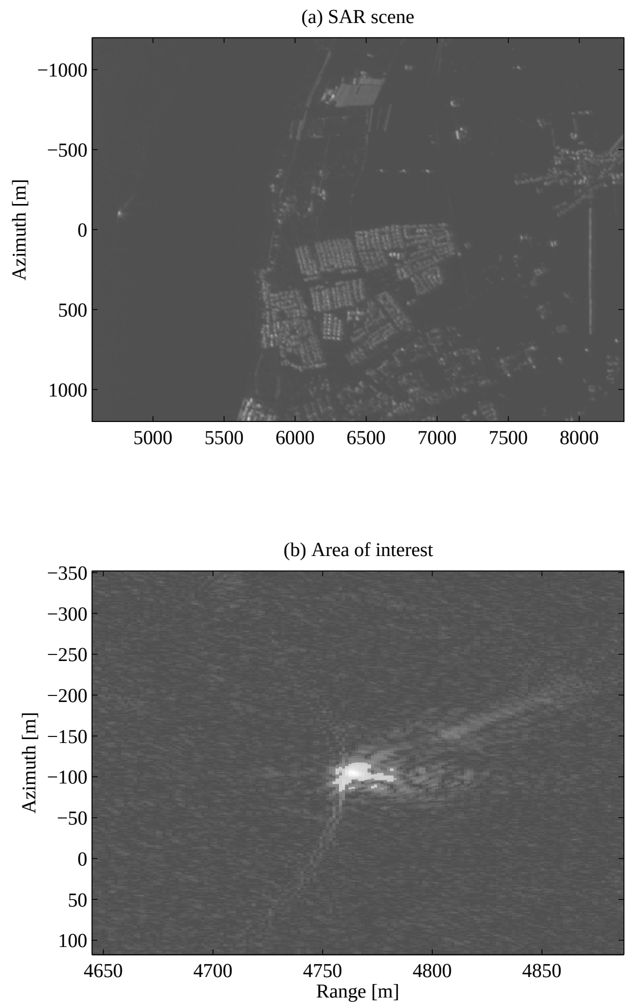

Fig. 6. The area surrounding the elliptical curve where the presence of a moving target with $\gamma = 0.96$ has been detected is extracted and processed separately before inserting back to the SAR image. The elliptical curve in the extracted area is now well focused to the original feature of the target. (a) SAR scene. (b) Area of interest.

focus the moving target correctly but the processing does not affect the other parts of the SAR image. Other parts of the SAR image are still well focused. Please note that the original SAR image is formed by the backprojection algorithm and this does not affect the performance of the proposed approach. The gain in processing time in comparison with processing the whole SAR image is now up to a factor of 182.

VI. Conclusion

A method for moving target focusing on SAR image is presented in detail in this paper. The method is based on the Range Migration algorithm and the normalized relative speed concept. The simulations results illustrate the method as well as show the advantages of the method in comparison to the previously proposed methods. The successfully experimental results verify the practicality of the method.

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