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SAR image formation enhancement using effective velocity estimation method

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SAR image formation enhancement using effective velocity estimation method

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Abstract: Synthetic Aperture Radar (SAR) presents powerful tools for grounding mapping and remote sensing applications. Effective velocity is a vital index that controls the quality of SAR image formation. An accurate calculation of effective velocity provides a particular value of azimuth frequency modulated (FM) rate. The resultant azimuth FM rate could be used to produce a focused SAR image with sharp details. In this paper, SAR image formation enhancement is proposed using two guided methods based on precise effective velocity estimation. Firstly, effective velocity is estimated based on Sentinel-1data parameters extracted from selected image raw data. Secondly, an iteration method applies output image contrast, sharpness and entropy measurements to estimate the optimum value of the effective velocity based on the initial velocities calculated in the first method. Results are compared with extracted SAR images ignoring the effect of the effective velocity, to identify the performance of the proposed methods.

1. Introduction

The demand of high resolution SAR image in military and civil applications is considered as one of the major requirements in recent days [1]. There are many algorithms for SAR image formation like range Doppler algorithm, chirp scaling algorithm, omega-K algorithm, and back projection algorithm [2, 3]. These algorithms are continuously modified and upgraded to improve SAR image formation process and image quality, which differ due to on-hand application [2-5].

The range Doppler algorithm (RDA) was the first image formation algorithm used for SAR processing. Nevertheless, it is still the most known used algorithm due to its efficiency, simplicity and accuracy[6]. In other hand, RDA uses time domain interpolation, which needs intensive computations to overcome range cell migration (RCM) problem [2, 4, 5]. The Chirp Scaling Algorithm (CSA) is developed mainly to overcome the shortages of range Doppler algorithm (RDA). However, RDA is the principal algorithm for several SAR image formation applications. While, CSA has several advantages compared with RDA and the other used algorithms. These advantages of CSA could be summarized as computation efficiency and easy to model [3, 4, 7-9].

The Omega-k algorithms (WKA) shares RDA the same weakness point of intensive computation problem due to interpolation processing. Moreover, its assumption that SAR effective velocity is range independent, which reflects on its ability to work with large swaths.

Now, we are going to introduce in details the basic schematic block diagram of CSA as shown in figure 1 [4, 10]. The main concept of CSA is the ability to implement Range Cell Migration Correction (RCMC) through phase multipliers [4]. Firstly, azimuth FFT is done to transform the two-dimensional time domain raw data from range time domain to range Doppler domain. Then, the first phase multiplication is done to cancel the range migration for all received echoes. Next, a range FFT is done to convert the signal into two-dimensional frequency domains. Then, a second phase multiplication is performed to apply range compression, and RCMC. The next step is to perform range IFFT to convert the signal back to range Doppler domain. Then, third phase multiplication is performed to apply azimuth compression. Lastly, an azimuth IFFT is performed to transform the compressed data again to the two dimensional time domain, which presents SAR focused image [4, 8, 10].

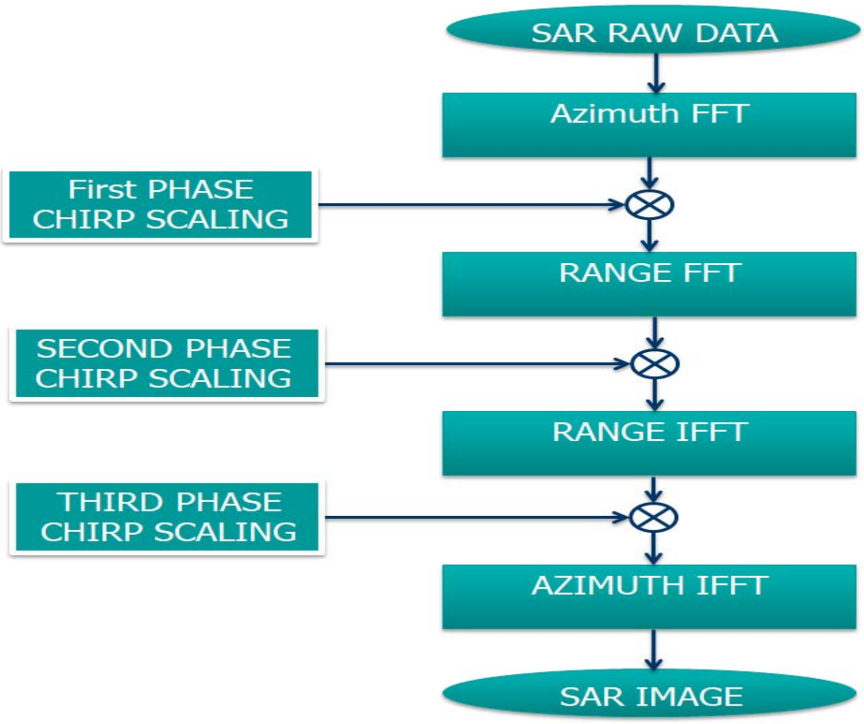


Figure 1. Basic block diagram of CSA

SAR image quality improvement is the fundamental objective for several SAR system designers [1, 3]. Conceptually, SAR image quality is guided by the precise calculation of the effective velocity [4, 11-13]. Theoretically, there are two system velocities [4]. One is the satellite/platform (radial) velocity, which presents the platform velocity along specific flight path. While, the other one is ground (beam footprint) velocity, which presents the sweep velocity of zero Doppler line along the ground as shown in figure 2 [4, 12, 13].

Based on radar slant range equation, the distance from SAR sensor to a target is calculated according to equation (1) [4, 12, 13]:

$$R(\eta) = \sqrt{R_o^2 + V_r^2\eta^2} \tag{1}$$

Where, R_o is the range of closest approach, η is the azimuth time (slow time), and V_r is the SAR effective velocity.

For spaceborne platforms, there is a difference between the radial and ground velocities, which equals approximately 12% [4]. However, these two velocities are almost the same for airborne platforms. Numerically, the velocity difference source for spaceborne case of study is the radius difference. Where, the satellite orbit is larger than the ground radius. Slant range equation supposes that the satellite moves in a straight line. Practically, this assumption is not true. In fact, the satellite rotates in a curvature orbit with a relative velocity, which is called as SAR effective velocity [4, 14].

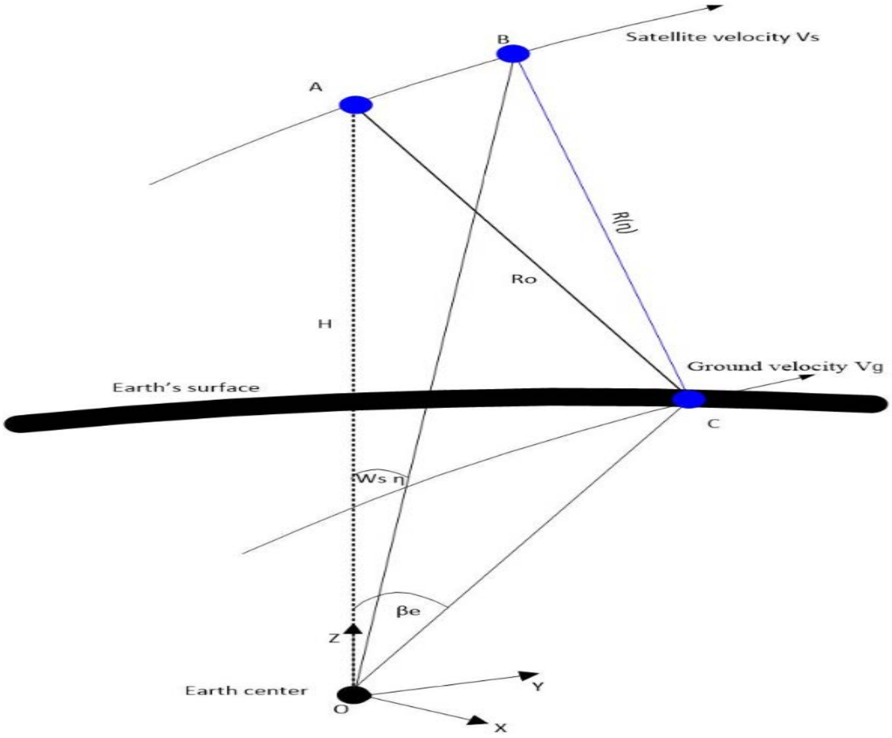


Figure 2. SAR Geometry for satellite velocity and beam footprint velocity presentation

The precise calculation of effective velocity is considered a critical parameter in producing a sharp focused image. Nevertheless, it is an effective parameter in calculating the azimuth FM rate, one of the powerful parameters that effects directly in image quality enhancement. Azimuth FM rate (K_a) could be estimated as follows:

$$K_a = \frac{2V_r^2 \cos^2(\theta_r)}{\lambda \, R(\eta)} \quad (2)$$

Where, θ_r is the squint angle, and λ is the antenna wavelength.

Based on the above equation of azimuth FM rate, it is obvious that, any error in estimating the effective velocity causes an error in azimuth FM rate. Moreover, it causes a matched filter phase error, which finally produces a low quality SAR image.

In this work, two methods are introduced to enhance SAR image quality based on the precise estimation of SAR effective velocity. In first method, the effective velocity is calculated numerically based on level-0 raw data[13]. While in the second method, an iteration algorithm is applied to precisely estimate the optimum effective velocity for optimal image enhancement. This method reflects a higher image quality calculated by its contrast, sharpness, and entropy [15].

The rest of this paper is organized as follows: in section 2, a numerical calculation for effective velocity estimation. Section 3 shows the iteration method used for the optimum effective velocity estimation. Finally, conclusion comes in section 4.

2. Numerical calculation of the effective velocity

Effective velocity (V_r) is numerically calculated based on mathematical derivation[13]. Firstly, satellite velocity (V_s) can be calculated by equation (3) guided by the extracted parameters after raw data treatment where, V_x, V_y, and V_z are the satellite velocities in the XYZ directions.

$$\mathrm{V_s} = \sqrt{\mathrm{V_x^2} + \mathrm{V_y^2} + \mathrm{V_z^2}} \tag{3}$$

Then, using the following equations in, the value of effective velocity could be numerically calculated.

$$\mathrm{H} = \mathrm{R_e} + \mathrm{h} \tag{4}$$

$$\mathrm{W_s} = \frac{\mathrm{V_s}}{\mathrm{H}} \tag{5}$$

$$\cos \beta_\mathrm{e} = \frac{\mathrm{R_e}^2 + \mathrm{H}^2 - \mathrm{R_o^2}}{2\,\mathrm{R_e}\,\mathrm{H}} \tag{6}$$

$$\mathrm{V_g} = \mathrm{R_e} * \mathrm{W_s} * \cos \beta_\mathrm{e} \tag{7}$$

$$\mathrm{V_r} = \sqrt{\mathrm{V_g} * \mathrm{V_s}} \tag{8}$$

Where, $\mathrm{V_g}$ is the ground velocity, H is the local orbit radius, $\mathrm{W_s}$ is the radial velocity, $\mathrm{R_e}$ is the local earth radius, h is Sentinel-1 orbit altitude, β_e is the angle of center earth, and $\mathrm{R_o}$ is the range of the closest approach, which could be obtained from the extracted raw data. Firstly , calculate the satellite velocity after Sentinel-1A raw data level-0 treatment , secondly, calculate the ground velocity by applying for example, Sentinel-1A parameters listed in table 1 in equations(4-7), finally, the effective velocity is calculated from equation (8). The calculated values of the three velocities are listed in table 2.

Table 1. Sentinel-1 parameters [16]

Parameter	Value	Unit
Local earth radius R_e	6378	km
Angle of centre earth β_e	0.0435	Rad
Sentinel-1 orbit altitude h	693	km
Local orbit radius H	7071	km

Table 2. Calculated velocities using numerical method

Parameter	Value	Unit
Satellite velocity $\mathrm{V_s}$	7589	m/s
Ground velocity $\mathrm{V_g}$	6839	m/s
Effective velocity $\mathrm{V_r}$	7200	m/s

3. Iteration method for optimum effective velocity estimation based on measuring the image contrast, entropy and, sharpness.

Conceptually, the satellite has a fixed altitude, and moves in a defined orbit with, approximately constant speed. From this point of view, the effective velocity could be also used as constant values during the whole flight path without degrading the image quality. The main advantageous of this concept is to reduce the processing time, which is a big issue in SAR systems but with a sensible reduction in SAR image quality [2].

To overcome on this problem, we need to find criteria that calculate the effective velocity precisely. It was found from previous research works that contrast, sharpness and entropy are widely used for image quality measurements. The iteration calculation of contrast, sharpness, and entropy as given in figure 3 are obtained based on results of the previous section.

As a result, the image quality is improved as the values of the contrast and sharpness increase[17, 18]. In the contrary, the image quality increases by minimizing the calculated entropy value [19]. Finally, the best output results from the three metrics lead to the precise value of the effective velocity at which, the optimal image resolution is obtained. The definitions of the three metrics are presented as follows: The ratio of the standard deviation to the mean of the image intensity named as image contrast [15]:

$$\mathrm{Co} = \frac{\sqrt{\mathrm{E}\{[\mathrm{I}^2(\mathrm{m},\mathrm{n}) - \mathrm{E}\{\mathrm{I}^2(\mathrm{m},\mathrm{n})\}]^2\}}}{\mathrm{E}\{\mathrm{I}^2(\mathrm{m},\mathrm{n})\}} \tag{9}$$

where, $\mathrm{I}(\mathrm{m},\mathrm{n})$ is the pixel intensity m=1,..M, n=1,..N, and E [●] is the mean value of the arithmetic mean of the samples and is defined by:

$$\mathrm{E}\{\mathrm{I}^2(\mathrm{m},\mathrm{n})\} = \frac{1}{MN}\sum_{m=1}^{M}\sum_{n=1}^{N} I^2(m,n) \tag{10}$$

The image sharpness could be obtained from convolving an image with Sobel operator, and sums the square of the gradient vector components as follows [15]:

$$\mathrm{SH} = \sum_{m} Height \sum_{n} Width\ (S_x(m,n)^2 + S_y(m,n)^2) \tag{11}$$

Where, $\mathrm{S_x}(\mathrm{m},\mathrm{n})$ and $\mathrm{S_y}(\mathrm{m},\mathrm{n})$ are the resultant image from convolution with Sobel summation.

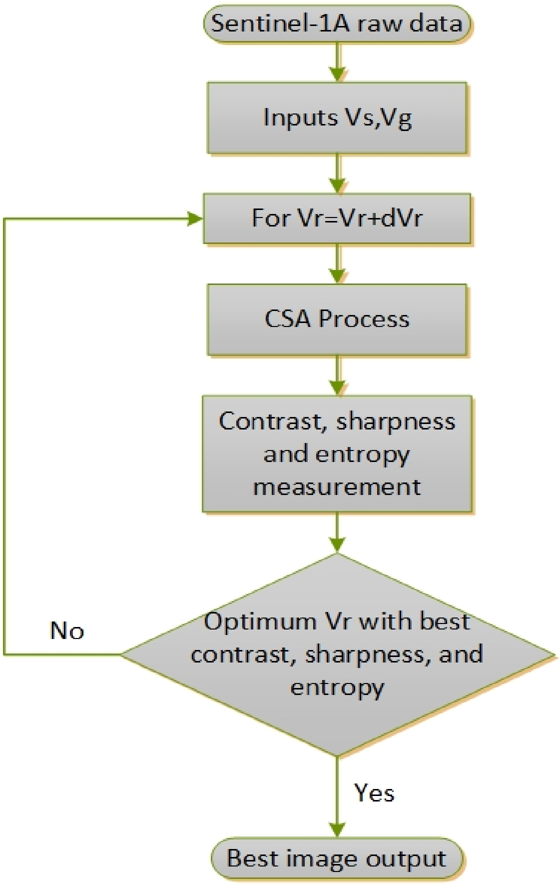


Figure 3. Effective velocity estimation flowchart based on iteration calculation of contrast, sharpness, and entropy

Finally, the image entropy could be expressed as follows [15]:

$$\mathrm{Ent} = -\sum_{m}\sum_{n}\left(\frac{\mathrm{I}^2(\mathrm{m},\mathrm{n})}{\mathrm{S}}\right)\ln\left(\frac{\mathrm{I}^2(\mathrm{m},\mathrm{n})}{\mathrm{S}}\right) \tag{12}$$

Where,

$$\mathrm{S} = -\sum_{\mathrm{m}}\sum_{\mathrm{n}}\mathrm{I}^2(\mathrm{m},\mathrm{n}) \tag{13}$$

The simulator parameters used in the modelled CSA are listed in table 3 [20] , and Sentinel-1A real raw data for a selected area shown in figure 4 are applied as an input raw data. The iteration process evaluates the values of contrast, sharpness, and entropy. This process continues for all the values of effective velocity between ground and satellite velocities calculated in previous section. The optimal obtained image resolution based on the metrics calculations leads to the precise effective velocity.

The results from numerical and iteration methods are compared with that obtained by ignoring effective velocity calculation is shown in Table 4. It is obvious that, the best-obtained result, which gives the better image quality, is obtained from using the iteration method.

Figure 4. Sentinel-1 preprocessed image raw data used in the proposed CSA

Table 3. Sentinel-1A SAR simulator parameters

Parameter	Value	Unit
Carrier frequency	5.504	GHz
PRF Range	1000-3000	Hz
RF peak power	4.141	Kw
Maximum Range Bandwidth	100	MHz
Antenna length	12.3	M

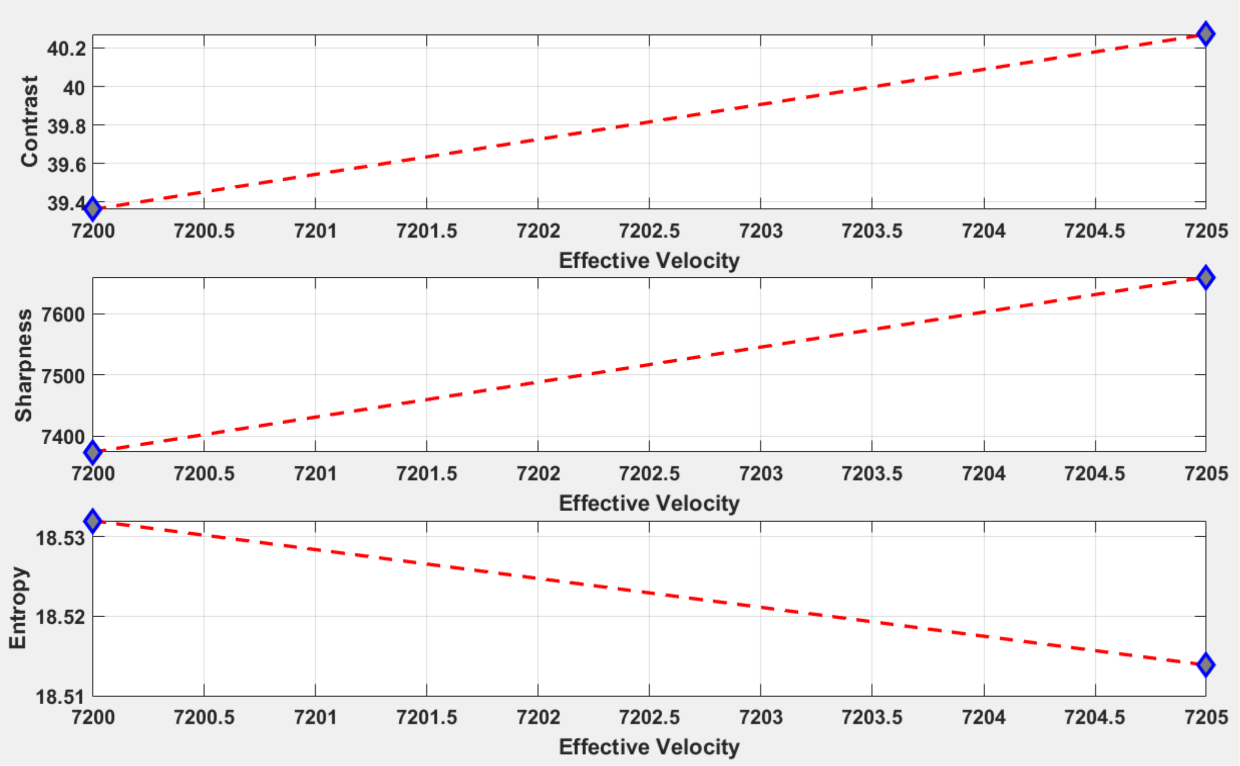
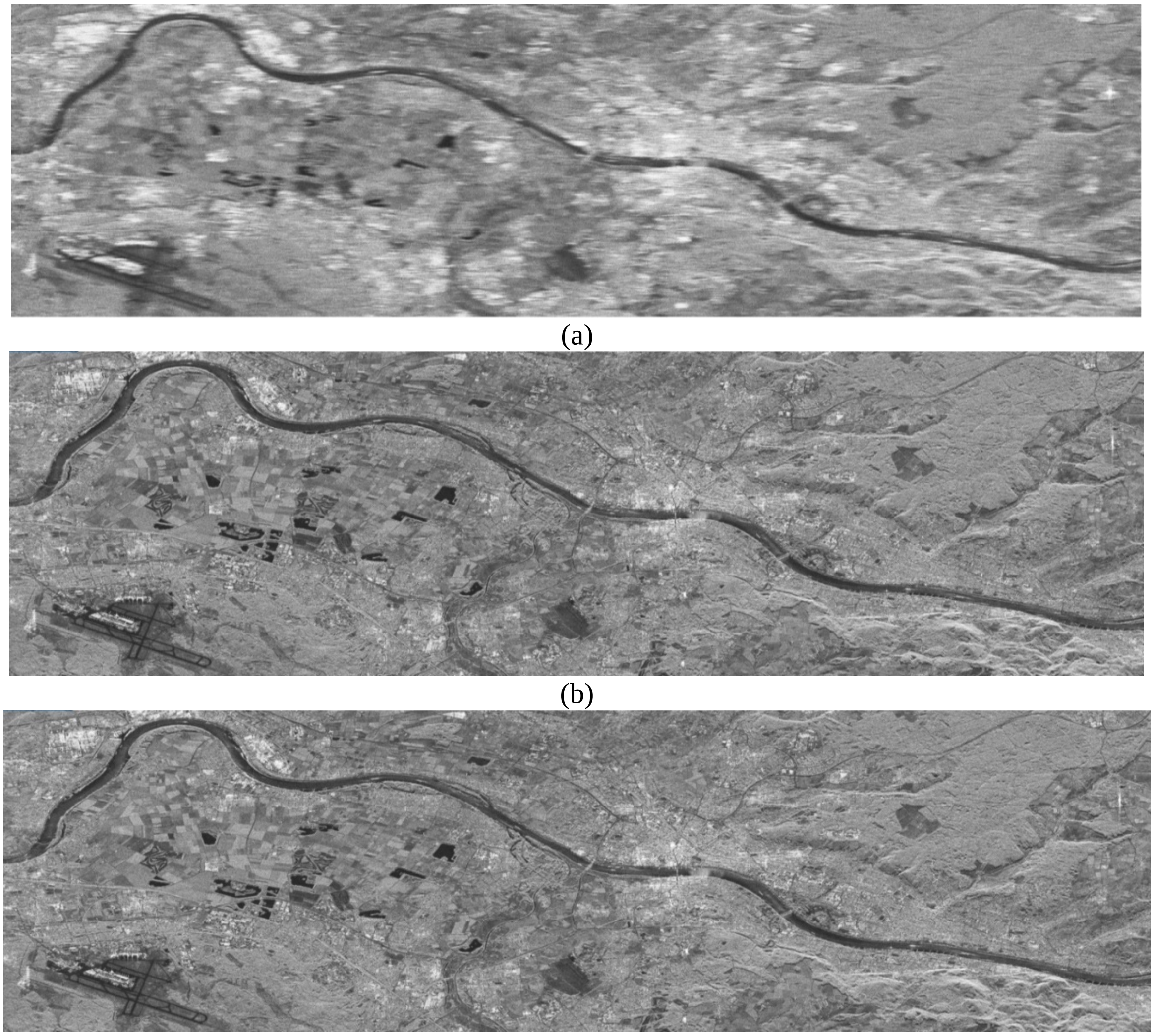


Figure 5. Iteration results (V_r= 7205 m/s) versus numerical results (V_r=7200 m/s) for image (a) contrast, (b) sharpness, and (c) entropy.

Table 4. Calculation of contrast, entropy and sharpness for the obtained values of effective velocity compared with ignoring effective velocity.

Metric parameter	Without effective velocity estimation $V_r = V_s$	With numerical calculation $V_r = 7200\ m/s$	With optimum iteration output $V_r = 7205$ m/s
Contrast	10.53	39.36	40.27
Sharpness	346	7374	7660
Entropy	18.96	18.53	18.51

Finally, the output images from applying the Sentinel-1A raw data in the modelled CSA at the three values V_r in table 4 is shown in figure 6. It is clear that, there is an improvement in the image quality. Where, image (a) is produced with ignoring effective velocity ($V_r = V_s$), image (b) is produced through using the numerical method result (V_r= 7200 m/s), while, image (c) is produced through using the iteration method result (V_r= 7205 m/s).



(a)

(b)

(c)

Figure 6. The output image from modelled CSA, (a) without effective velocity estimation, (b) with effective velocity enhancement using numerical calculation (V_r = 7200), and (c) with effective velocity enhancement using the proposed iteration method (V_r=7205 m/s).

4. Conclusion

The work in this paper investigates the effectiveness of the accurate calculation of effective velocity on SAR image formation enhancement. An Iteration method for optimum effective velocity estimation based on measuring the image contrast, entropy and, sharpness is developed. Simulation of the proposed algorithm is applied on Sentinel-1A real raw data of a selected area. The study explores that the accurate calculation of effective velocity provides a particular value of azimuth frequency modulated (FM) rate which lead to produce a focused SAR image with sharp details. An additional study is needed on the optimization to restrain the high computational cost.

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