Multi-Look SAR Processing with Road Location and Moving Target Parameters Estimation

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Abstract: Multi-look processing is a well-known technique actively used in the SAR research community. In the paper, a method is described for the extraction of the ground moving targets parameters from a sequence of SAR look images obtained with a single-antenna SAR. The method calls for the automatic road extraction from the multi-look SAR images. The proposed road detection and location algorithm is based on the Canny edge detector and the histograms of image gradient directions. The estimated road coordinates are used for unambiguous evaluation of the moving targets parameters, namely the velocity components and the coordinates.

1. Introduction

Synthetic aperture radar (SAR) is a very popular instrument for high-resolution imaging [1]-[3]. In the recent decade, the interest for various applications of this radar technique has been growing rapidly. In particular, different methods such as object detection and recognition in SAR images, feature extraction, automatic moving target indication are on a great demand for both civil and industrial applications. All these methods require the usage of both signal and image processing algorithms.

The problem of moving targets detection is well-known [4]-[8]. One of possible solutions of this task is based on the analysis of a sequence of single-look SAR images. The basic idea is that the moving targets appear at different locations in the consequent SAR looks. Therefore, one can estimate the target displacements and use them for the extraction of moving targets parameters at the next step. However the challenge is that in the case of target detection with a single-antenna SAR, there is an ambiguity in determination of the target position and velocity [7].

In the paper, the method for the automatic road detection and location, and moving target parameters estimation is proposed. It is based on the analysis of the SAR image edge map and gradient directions. As the result, the locations of road segments can be evaluated. Then, the extracted data is used for unambiguous estimation of the moving targets parameters. Such combination of the road detection methodology and the equations derived for the moving targets analysis allows to estimate both moving target velocity and position.

In Section II, the main principles of the moving targets detection on a sequence of SAR looks are described. The road detection and location approach is considered in Section III. Details of the proposed moving targets parameters extraction framework are discussed in section IV.

2. Moving Targets and SAR Processing

The commonly used SAR processing algorithms [3], [9] are intended for the formation of a SAR image of a static ground scene. It is well-known that ground moving target echoes appear defocused and displaced to wrong positions in the SAR images [7]-[8]. Such behavior of the moving target has been utilized in the recently developed method for the detection of moving targets and estimation of their parameters [7]. It has been found that there is an ambiguity between the target velocity and target position within the antenna footprint. In order to resolve the ambiguity, the direction of the target motion or, in other words, the orientation of the target velocity vector is required. Assuming that the considering ground moving targets are vehicles on the roads on the scene, the direction of the target motion can be derived from the orientations of the roads. Below in this section, the main principles of the moving target detection method [7] are briefly described.

The aircraft with the SAR system aboard is assumed to fly at the altitude $z = H$ above the x axis of the ground plane (xy) with the velocity V_a. A sequence of SAR look images are formed by processing the radar data collected on the time intervals $[t_n - T_s/2, t_n + T_s/2]$, where T_s is the time of synthesis, t_n are the centers of the intervals that corresponds to the aircraft positions $V_a t_n$, and n is the indexes of the SAR looks.

The target is moving within the ground plane (xy) with a constant velocity $\vec{\mathbf{v}} = (v_x, v_y)$. At the moment of time $t = 0$ (when the aircraft is exactly above the origin of the coordinate system) the target position is (x_T, y_T). If the moving target echo is detected at the position (x_n, y_n) on the n-th SAR look and then it is displaced into the position (x_m, y_m) on the m-th SAR look, then the following parameters of the moving target can be estimated:

1) the range to the target at the moment $t = 0$

$$R_T^2 = (R_n^2 + R_m^2)/2\,, \quad \vec{\mathbf{R}}_T = (x_T, y_T, -H)\,, \tag{1}$$

$$R_{n,m}^2 = x_{n,m}^2 + y_{n,m}^2 + H^2 - \frac{x_m - x_n}{t_m - t_n} V_a t_{n,m}^2\,,$$

2) the module of the relative target velocity,

$$V^2 = V_a^2 - V_a \frac{x_m - x_n}{t_m - t_n}\,, \quad \vec{\mathbf{V}} = \vec{\mathbf{V}}_a - \vec{\mathbf{v}} = (V_a - v_x, -v_y, 0)\,, \tag{2}$$

3) the radial component of the relative target velocity

$$(\vec{\mathbf{R}}_T \cdot \vec{\mathbf{V}}) = V_a \frac{x_n t_m - x_m t_n}{t_m - t_n}\,. \tag{3}$$

As far as the values of R_T^2, V^2 and $(\vec{\mathbf{R}}_T \cdot \vec{\mathbf{V}})$ are estimated, the following three equations can be written to find the velocity components v_x, v_y and the coordinates x_T, y_T of the target:

$$x_T^2 + y_T^2 = R_T^2 - H^2\,, \tag{4a}$$

$$(V_a - v_x)^2 + v_y^2 = V^2\,, \tag{4b}$$

$$x_T(V_a - v_x) - y_T v_y = (\vec{R}_T \cdot \vec{V})\,. \tag{4c}$$

In order to find the four unknowns (v_x, v_y, x_T, y_T) from (4), the forth equation is required; otherwise there is the ambiguity “target position – target velocity”.

If we can recognize the road on the scene, on which the target is supposed to be moving then we can supplement the above equations with the estimated target road equation

$$y = kx + b\,,$$

so that the target velocity components are related as

$$v_y = k v_x\,. \tag{5}$$

In the subsequent sections it is shown how unknown moving targets positions and velocities can be properly estimated using the sequence of detected road segments and introduced equations.

3. Roads Detection

SAR images have different properties in comparison to optical images. The reason is in the SAR image formation process that is accomplished via coherent processing of the received signals backscattered from the Earth surface. As a result, the multiplicative speckle noise appears in the SAR images [1]-[4]. It complicates the analysis of the image content and extraction of the features of interest.

In the paper, we consider the task of road detection and location in SAR images. A number of various road detection approaches have been developed so far [10]. Some of them are fully autonomous and automatic, the rest are based on some known information and data.

The main idea of the road detection is related with the fact that the road has some principal features. First, the roads appear in SAR images as linear segments with different inclinations that do not change significantly. Second, the length of the road is much greater than the width, and the width of the road is approximately constant. Other important properties are related with the intensity of road pixels. In particular, the pixel intensity gradient along the road is approximately constant, while the intensity gradient across the road can vary significantly. In this section, we propose the way how the gradient direction can be used for the automatic road detection.

Let us consider an example of the multi-look spaceborne SAR image (Fig. 1a) [11]. In the image, several road segments are observed together with other objects and different textures.

The road detection algorithm is as follows. At the first stage, the bilateral filter [12] is applied for the initial preprocessing and noise suppression. This filter is based on both spatial and range weighting of the image pixels. The bilateral filter weights are determined as

$$w(i,j,k,l) = e^{-\frac{(i-k)^2+(j-l)^2}{2\sigma_d^2}} e^{-\frac{(I(i,j)-I(k,l))^2}{2\sigma_r^2}},$$

where the first term corresponds to the spatial weighting with variance σ_d^2, and the second term is related with the intensity range weighting with variance σ_r^2. Thus, the filtered image can be calculated as follows:

$$I_b(i,j) = \sum_{k=1}^{Nw}\sum_{l=1}^{Nw} I(k,l)w(i,j,k,l) / \sum_{k=1}^{Nw}\sum_{l=1}^{Nw} w(i,j,k,l).$$

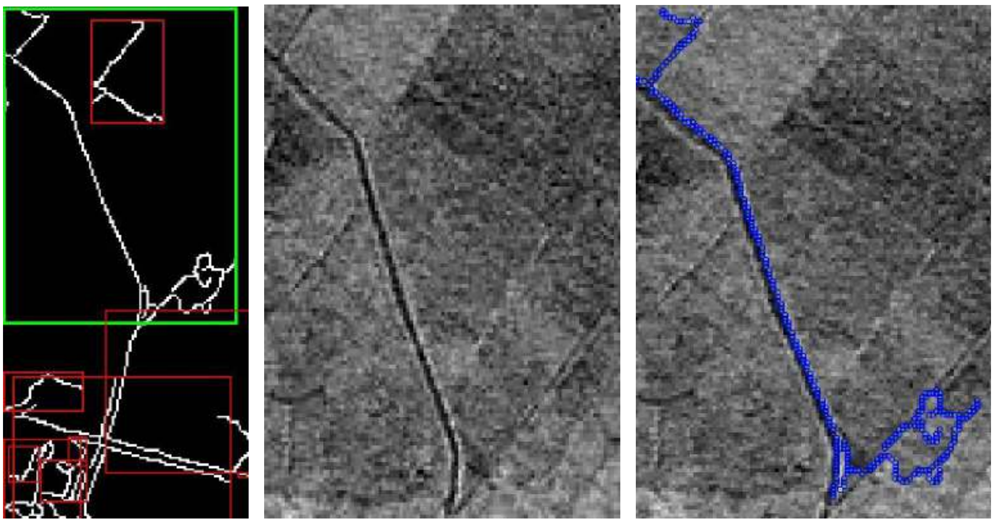
Fig. 1b shows an example of the bilateral filtering.

(a) (b)

Figure 1. SAR image preprocessing using bilateral filter:
(a) – input SAR image, (b) – image after bilateral filtering.

After comparison of the images in Fig. 1 one can observe that most of small unnecessary details have been filtered out. At the next step, the edge detection is performed. The result of the Canny edge detector [13] application is illustrated in Fig. 2a. The color rectangles in this image correspond to the bounding boxes of the detected connected components. One can observe that some of the rectangles contain the road segments while the others do not.

Fig. 2b contains an example of the image patch corresponding to one of the connected components (the green rectangle in Fig. 2a). The list of the pixels belonging to this area is marked in blue.



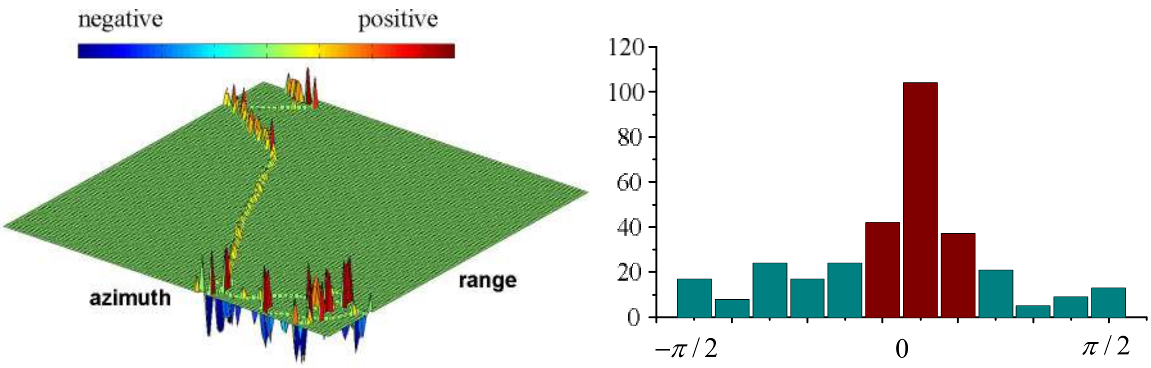
(a) (b)

Figure 2. Illustration of detected edges and connected components:
(a) – edge map with the connected components bounding boxes,
(b) – example of the pixel list for a single connected component.

The proposed idea is related with the fact that the image gradient directions at the road edges are preserved approximately constant along the road. In other words, the road segment can be detected as a sequence of pixels with the constant gradient directions. The image gradient direction θ_{ij} can be calculated as

$$\theta_{ij} = \operatorname{atan}(I_y / I_x),$$

where I_x, I_y are the horizontal and vertical image gradients [13] respectively. Fig. 3a illustrates an example of the gradient direction map for the connected component given above.



(a) (b)

Figure 3. Analysis of gradient directions:
(a) – 3D diagram of gradient directions, (b) – histogram of gradient directions.

One can observe that there are some areas where the direction is preserved constant. The calculated histogram of the gradient directions is shown in Fig. 3b. One can clearly see that some main gradient directions can be chosen (red columns). We propose to reject all the pixels that belong to the histogram bins that do not make significant contribution and leave only those pixels that correspond to the main directions of the histogram. Such pixel filtering procedure should be applied for each connected component separately. At the next step, the described histogram filtering is accomplished for all pixels that are left after the connected components analysis. Finally, the grouping of pixels with equal gradient directions is accomplished resulting in detection of linear road segments.

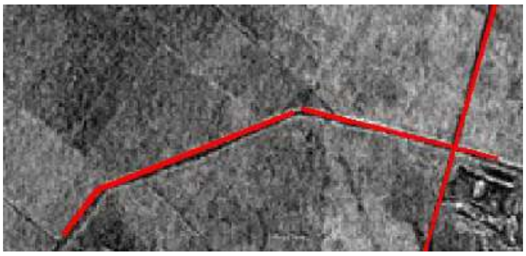


Figure 4. Result of the developed road detection algorithm.

Fig. 4 illustrates an example of the detected road segments. In the next section, the framework of the moving targets parameters estimation with the proposed road location algorithm is considered.

4. Framework for Moving Targets Parameters Extraction

The described ideas of the moving target analysis and road detection can be combined together into an efficient algorithm (Fig. 5).

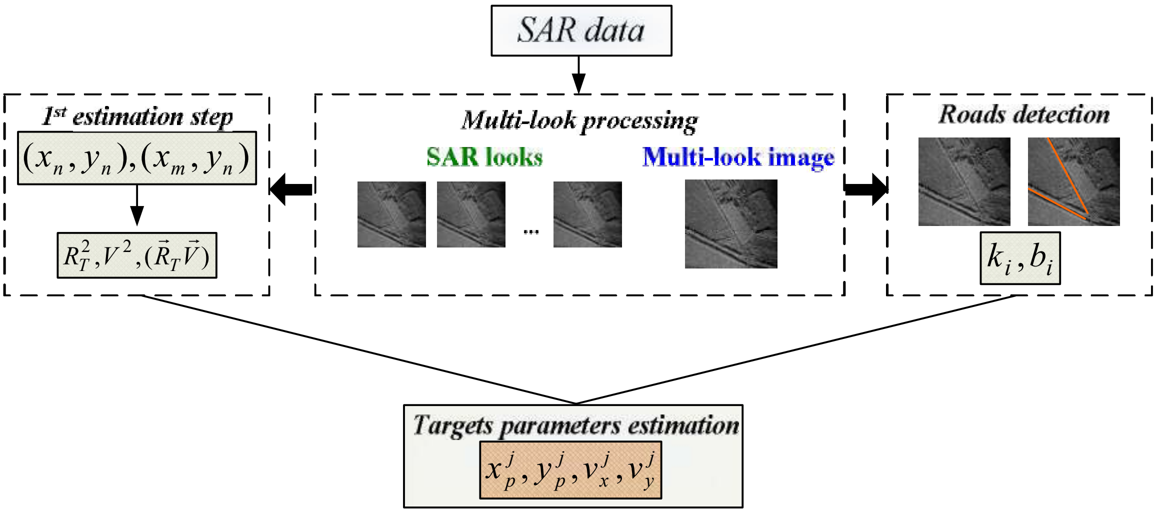


Figure 5. Block-scheme of proposed method.

We assume that all necessary SAR raw data preprocessing steps are applied, in particular, the common motion compensation procedure based on the navigation data, as well as the residual phase error correction with autofocusing [2], [14]. By multi-look SAR processing, one can obtain the sequence of SAR looks and the resulting multi-look SAR image that is used as the input for the road detection algorithm. The sequence of the SAR look images is used for the detection of the moving targets on the scene. Based on this the first estimation step is performed resulting in extraction of slant ranges to the targets (1), absolute velocity values (2) and the radial velocity components (3). At the same time, the sequence of the road segments (k_i, b_i) is extracted from the multi-look SAR image.

It is shown [7] that from (4) and (5) two possible solutions can be found for the target velocity and the total four possible solutions can be found for the target position. In order to choose the one appropriate solution from these four solutions, one should use some additional information. In particular, we can filter out unrealistically fast targets and reject the solutions outside the real antenna footprint. Also, for each moving target one can find the closest road by minimizing the following expression

$$m_i^j = \left| b_i - (y_p^j - k_i x_p^j) \right|, \quad (6)$$

where m_i^j is corresponding metrics for i^{th} road and j^{th} target. Thus, that if there are more than one road in the scene, the crossroads etc. then one should analyze all possible solutions for all detected road equations and select the one road according to (6). As a result, the moving targets parameters can be properly estimated.

The developed moving target analysis framework can be used in real SAR systems for efficient extraction of moving targets parameters using single-antenna configuration.

5. Conclusion

In the paper, the methodology for the automatic road detection based on histograms of gradient directions is proposed. Extracted road parameters can be used for unambiguous estimation of velocity and locations of moving targets. Corresponding analytical derivations are described together with important theoretical ideas. Developed technique can be used for the extraction of moving targets characteristics from SAR data with a single-antenna SAR system.

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