A Novel Algorithm for Estimation of Moving Target Parameters with Single-Antenna SAR

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***Abstract*— the idea for automatic extraction of the moving target parameters using single-antenna synthetic aperture radar is proposed. The displacements of the target are estimated from the sequence of the single-look SAR images using the Lucas-Kanade optical flow technique. It is shown that both moving target location in the SAR look and its shift direction can be extracted. In addition, the linear road segments are automatically detected from the multi-look SAR image using the Canny edge map and local pixels intensity gradient analysis. Proposed ideas are incorporated into the novel algorithm capable to unambiguously extract the moving target parameters using the single-antenna SAR system. Experimental examples obtained with X-band airborne SAR system are illustrated as well.**

Keywords—synthetic aperture radar; multi-look processing, moving targets, road detection, optical flow

I. Introduction

Synthetic aperture radar (SAR) is a well-known instrument for high-resolution imaging [1]-[4]. Incorporation of modern signal and image processing solutions makes it a superior tool for various remote sensing tasks. In addition, the fast development of the hardware solutions allows to construct the high-resolution multi-look SAR images onboard in real-time.

The analysis of moving targets is a popular research problem [5]-[7]. It is known that the moving objects appear as shifted and defocused in resulting SAR images [5]-[7]. One of possible solutions in this case is based on the analysis of SAR looks sequence. The challenge is that in the case of single-antenna SAR system, the ambiguity “target velocity-target position” arises [7]-[8]. In order to solve this problem, we propose to extract the additional information from single-look and multi-look SAR images.

In the paper, we propose several ideas for the moving targets parameters extraction. At first, the algorithm for automatic road location is proposed. This is done via the Canny edge map [9] and local intensity gradient analysis in the multi-look SAR image. In addition, we demonstrate the potential of the optical flow techniques for automatic estimation of the target displacements from a sequence of SAR looks.

In Section II, the problem of the moving target parameters estimation is formulated. Proposed ideas for automatic road location and target shift extraction are described in Section III. Examples of real SAR images analysis obtained with X-band SAR system [10]-[11] are illustrated in Section IV.

II. Moving Targets and SAR Imaging

It is known, that the SAR processing is accomplished as a matched filtering [4]. In the case of a static ground scene and fully compensated sensor trajectory [3], [12], a well-focused multi-look SAR image is built. However where there is some kind of movement in the scene, the moving objects become smeared in multi-look SAR images [7]. Let’s consider a simple scenario of SAR geometry (Fig. 1). It is assumed that the SAR platform is moving along straight line at altitude H with constant velocity V_a. A sequence of SAR images is formed 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 intervals for each SAR look. The target is moving in the ground plane along the straight line $\vec{r}_T(t) = \vec{r}_T + \mathbf{v}t$ with a constant velocity $\mathbf{v} = (v_x, v_y, 0)$. Since the SAR processing is accomplished as the matched filtering with respect to the static targets, the resulting image of the moving target is appeared as shifted and defocused [7]. Using the above problem formulation, one can derive the following expressions

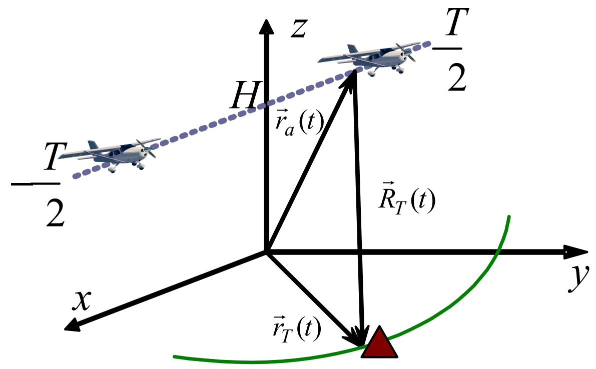


Figure 1. Basic SAR geometry

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

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

$$V^2 = V_a^2 - V_a \frac{x_m - x_n}{t_m - t_n} , \ \vec{\mathbf{V}} = (V_a - v_x, -v_y, 0) \quad (1b)$$

$$(\vec{\mathbf{R}}_T \cdot \vec{\mathbf{V}}) = V_a \frac{x_n t_m - x_m t_n}{t_m - t_n} , \quad (1c)$$

where (x_n, y_n), (x_m, y_m) are the target echo positions in n^{th} and m^{th} SAR looks respectively, R_T^2 is the range to the target, V^2 is the module relative target velocity and $(\vec{\mathbf{R}}_T \cdot \vec{\mathbf{V}})$ is the radial component of the relative target velocity. The problem is that there are 4 unknowns (v_x, v_y, x_T, y_T) and only 3 equations (1). As a result, the "target velocity-target position" ambiguity arises. Fortunately, it was shown [7]-[8] that in the case of location of the road corresponding to the particular target movement, both true target position and velocity can be retrieved. In the next section we briefly describe the developed road location method and also demonstrate how the moving target positions in the SAR look sequence can be automatically extracted.

III. Automatic Road Location and Estimation of Target Displacements

A. Approach for Road Location

In order to detect the road segments in SAR images, some principal features of the roads can be accounted. Firstly, the length of the road is much greater than the width. Secondly, the pixel intensity gradient is approximately constant along the road, but changing across it [13]. Fig. 2 illustrates an example of spaceborne SAR image [14] with road segments.

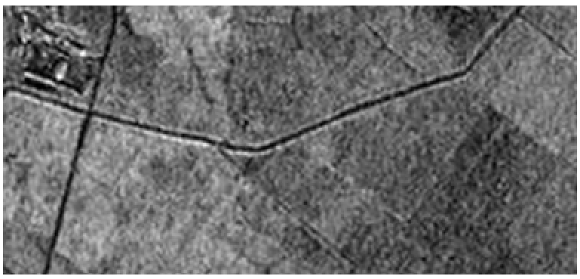
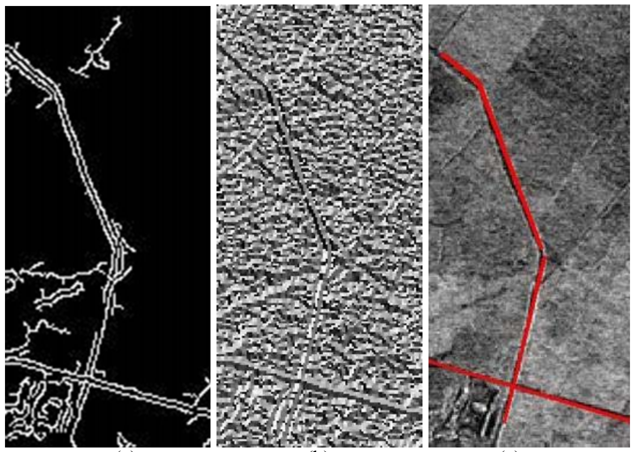


Figure 2. Cross-correlation maxima and defocused SAR image

Since the SAR image contains the speckle noise, the common approaches for the image analysis in the optical band should be modified accordingly [8]. In order to locate the road segments, we propose to use not only the intensity gradient magnitude distribution, but its direction as well.



(a) (b) (c)

Figure 3. Road detection steps
(a – Canny edge map, b – gradient directions, c – image with detected roads)

After the initial filtering of the high-frequency noise, the Canny edge map of the SAR image is calculated (Fig. 3a). One can observe that the road segments are visible in the edge map. In order to filter out unnecessary pixels, we developed the algorithm based on the analysis of the gradient direction histograms [8]. According to the method, the gradient direction distributions are analyzed in a set of detected connected components. A specifically developed pixels analysis procedure allows to filter out the unnecessary pixels. More detailed description of the road location approach can be found in [8].

In order to extract the moving targets, both road locations and the target positions in single-look SAR images should be known. Next subsection contains the description of how such movement is automatically extracted.

B. Optical Flow Estimation

It was shown above that for extraction of the moving target parameters its locations in the SAR looks sequence should be found. We propose to make this step to be automatic using the optical flow (OF) methodology [9], [15]. The OF methods are typically used in the optical band for detection of the object motion from the images sequence. The main assumption of this technique is an intensity preservation during the movement of the object pixel. This can be written as follows

$$I_m(x, y, t) = I_n(x + dx, y + dy, t + dt) , \quad (2)$$

where (x, y) is the pixel coordinates, m, n are indexes of images pair. Expanding (2) into the Taylor series gives a simple equation

$$I_x u + I_y v + I_t = 0 , \quad (3)$$

where I_x, I_y are the spatial gradients [9] of the image, $I_t = I_n - I_m$, $u = dx/dt, v = dy/dt$. One can see from (3) that we have two unknowns. In order to solve this problem, the OF is estimated within a particular local window around the given pixel. In our analysis we used the Lucas-Kanade technique which returns the OF vector as a solution of system of linear equations in the local window [9].

In our consideration, two single-look SAR images are used as input for the OF analysis. Fig. 4 illustrates an example of two SAR looks (1m resolution) and surface plot of the estimated OF.

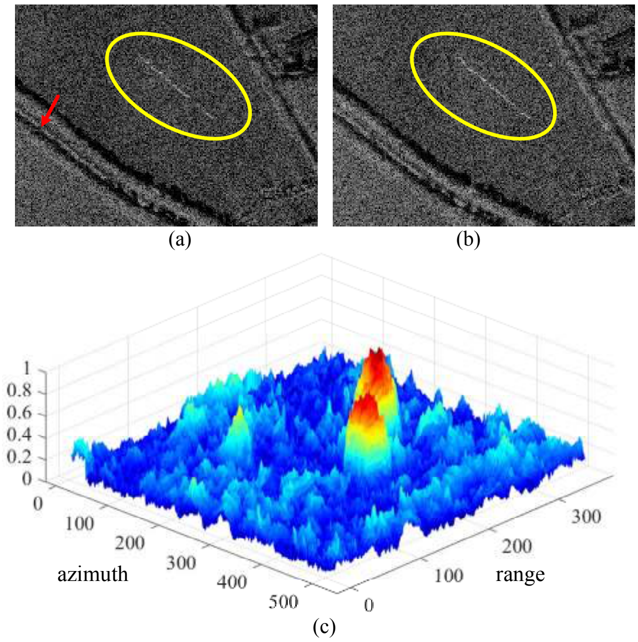


Figure 4. Optical flow surface
(a – first SAR look, b – second SAR look, c – optical flow surface)

In Fig. 4a the railroad is indicated by the red arrow. The train appears beyond it (yellow ellipse). The optical flow surface is shown Fig. 4c. One can observe multiple local peaks. Two peaks correspond to the moving train. Other peaks in Fig. 4c are caused by the existence of the speckle noise and the movement of the trees due to the wind. Also the amplitudes of pixels in SAR looks are modulated by the real antenna pattern, which affects on images histograms as well. Obviously, this may lead to false detections. In the next section it is shown how to utilize the OF for both target positions estimation and movement direction extraction. These steps are illustrated with real SAR images obtained with the RIAN-SAR-X system [10].

IV. Experimental Analysis

The moving target parameters estimation requires the knowledge about its positions (x_n, y_n), (x_m, y_m) in single-look SAR images. For this purpose we developed the algorithm based on the optical flow magnitude and direction analysis. At first, let's consider an example of a single-look SAR image with moving train (Fig. 5a). It is very difficult to

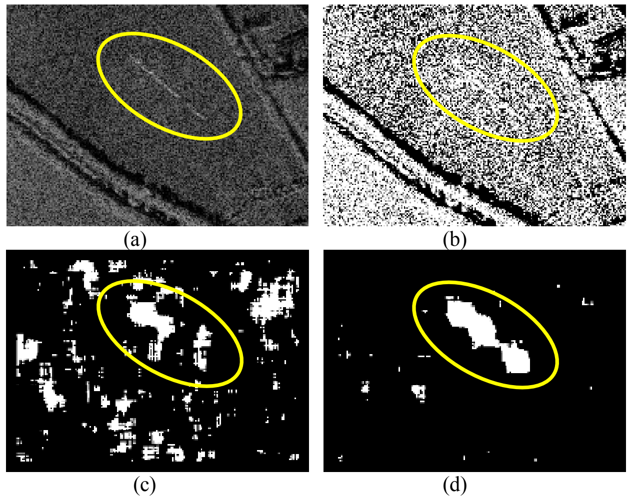


Figure 5. Example of moving train detection using optical flow
(a – SAR image, b – SAR image after binarization,
c – OF binary image, d – OF binary image with preprocessing)

detect it directly. For example, Fig. 5b contains the same SAR look after the application of the constant binary threshold. One can see that the target of interest is contaminated by the noise. In order to detect the moving train, the estimated OF magnitude image can be used. The application of thresholding in this case results in the image shown in Fig. 5c.One can observe a lot of blobs of different size. In order to increase the efficiency, two important step are applied. At first, the histograms of both SAR looks are adjusted according to the histogram of the multi-look image. We have found that in this case the result is better than in the case of direct histogram adjustment of two single-look images. After this the speckle filtering is performed [16]. Fig. 5d illustrates the binary image of the OF magnitude with application of described preprocessing. One can observe that the blob corresponding to the train is clearly seen. Thus, the moving object is detected using the OF magnitude image. One should emphasize that the target blob in the second image can be found in the similar way using the reverse OF estimation. Since the real targets commonly have complex shapes, an approximate locations in SAR looks (x_n, y_n) can be estimated as the mass centers of the corresponding blobs

$$x_n^C = \frac{\sum_x \sum_y x I(x,y)}{\sum_x \sum_y I(x,y)}, \quad y_n^C = \frac{\sum_x \sum_y y I(x,y)}{\sum_x \sum_y I(x,y)}, \qquad (4)$$

where $I(x,y)$ are image pixels within the blob area.

In principle, the estimated centroids (x_n^C, y_n^C), (x_m^C, y_m^C) can be used for the calculation of the moving target parameters. However, the problem is that that distributed targets demonstrate the dependence of the cross-section as a function of a view angle. In other words, the shapes of real targets may change for different SAR looks resulting in varying blob size in the preprocessed OF images (Fig. 5d). In order to make more robust moving target positions estimation, we propose to make two important steps. At first, the target shift direction is estimated. For this purpose we propose to analyze the histogram of the OF directions (Fig. 6).

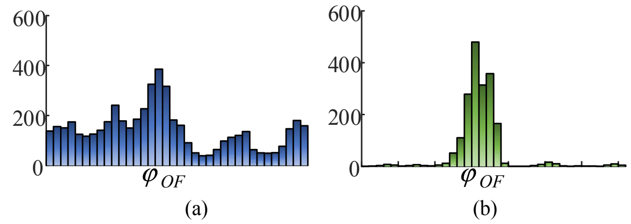


Figure 6. Real target shift direction extraction using optical flow
(a – histogram without preprocessing, b – histogram with preprocessing)

Fig. 6a and Fig. 6b illustrate the distribution of the OF directions before and after SAR images preprocessing. One can clearly see that the main optical flow direction is more visible after histogram adjustment and speckle filtering. The second step is to estimate the position of the moving target in the second image. The idea is quite straightforward. Based on the detected moving target positions in two SAR looks and the main OF direction, its position in the first image is taken as a centroid (x_n^C, y_n^C), while the position in the second image $(\widetilde{x}_m, \widetilde{y}_m)$ is found as the intersection point between the OF direction line and the main axis of the ellipse fitted into the target blob. Such approach allows to estimate the real moving target position in efficient way.

Proposed ideas have been combined into the framework for the automatic extraction of moving targets parameters. Fig. 7 contains the main steps for the target positions estimation. At first, the pair of SAR images is preprocessed: histograms are adjusted and speckle suppression filter is applied. At the next step an optical flow is estimated using the Lucas-Kanade algorithm. Application of a thresholding step leads to a sequence of detected blobs in the OF binary image (Fig. 5d). Then the main direction of the OF is extracted from its direction histogram. Finally, the moving target positions in both SAR looks are estimated. At the same time, the road segments are located from the constructed multi-look SAR image [8]. Since the extracted target positions and located road segments can be simultaneously used for the unambiguous estimation of the moving target parameters with the single-antenna SAR, proposed method allows to estimate all required parameters automatically.

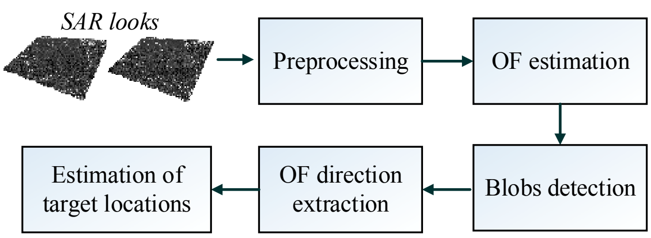


Figure 7. Main steps for target positions estimation

V. CONCLUSION

In the paper, the algorithm for the extraction of the moving target parameters is proposed. It is demonstrated that the moving target displacements can be estimated using the optical flow analysis. The moving object location in the SAR look and the direction of its shift are automatically extracted using the specifically developed procedure. In addition, the approach for the location of the road segments is described. Proposed framework can be used in modern single-antenna SAR systems for estimation of moving target parameters.

REFERENCES

[1] C. Oliver and S. Quegan, Understanding Synthetic Aperture Radar Images. Norwood, MA: Artech House, 1999.

[2] G. Franceschetti and R. Lanari, Synthetic Aperture Radar Processing. CRC Press, 1999.

[3] W. G. Carrara, R. S. Goodman, and R. M. Majewski, Spotlight Synthetic Aperture Radar: Signal Processing Algorithms. Boston; London: Artech House, 1995.

[4] I. G. Cumming and F. H. Wong, Digital Processing of Synthetic Aperture Radar Data: Algorithms and Implementation”. Norwood, MA: Artech House, 2005.

[5] Xu R., Zhang D., Hu D., Qiu X., Ding C, “A novel motion parameter estimation algorithm of fast moving targets via single-antenna airborne SAR system”, IEEE Trans. Geoscience and Remote Sensing Letters, Vol. 9, No. 5, pp. 920-924, 2012.

[6] Kirscht M., “Detection and imaging of arbitrarily moving targets with single-sensor SAR“, IEEE Proceedings Radar Sonar & Navigation, Vol. 150, No. 1, pp. 7-11, 2003.

[7] O.O. Bezvesilniy, B.A. Kochetov and D.M. Vavriv, “Moving target detection with multi-look SAR”, Proceedings of the 20th International Conference on Microwaves, Radar and Wireless Communications (MIKON 2014), Gdansk, Poland, Vol. 2, pp.559-562, 2014.

[8] I.M. Gorovyi, O.O. Bezvesilniy and D.M. Vavriv, “Multi-Look SAR Processing with Road Location and Moving Target Parameters Estimation “, Proceedings of the 16th International Radar Symposium (IRS 2015), June 23-26, Dresden, Germany, Vol. 1, pp.581-586, 2015.

[9] G.Bradsky and A.Kaehler, Learning OpenCV, O'Really Media Inc., 2008.

[10] D. M. Vavriv at al., “X-band SAR system for light-weight Aircrafts”, Proc. 15th Int. Radar Symp. IRS-2014, Gdansk, Poland, pp. 501–505, 2014.

[11] O.O. Bezvesilniy and D.M. Vavriv, “Synthetic Aperture Radar Systems for Small Aircrafts: Data Processing Approaches,” in Recent Advances in Aircraft Technology (edited by R.K. Agarwal), ISBN 978-953-51-0150-5, chapter 20, pp. 465-498, InTech, 2012.

[12] O.O. Bezvesilniy, I.M. Gorovyi and D.M. Vavriv, “Estimation of phase errors in SAR data by local-quadratic map-drift autofocus”, Proc. 13th Int. Radar Symp., Warsaw, Poland, pp. 376-381, 2012.

[13] J. B. Mena, “State of the art on automatic road extraction for GIS update: a novel classification”, Pattern Recognition Letters, Vol. 24, pp. 3037-3058, 2003.

[14] W. Pitz and D. Miller, “The TerraSAR-X Satellite”, IEEE Trans. on Geosc. And Remore Sens., Vol. 48, No. 2, pp.615-622, 2010.

[15] A. Plier,E. Colin-Koeniguer and F.Weissberger, A new coregistration algorithm for recent applications on urban SAR images, IEEE Geisc. And Remote Sens. Letters, Vol. 12, No. 11, 2015, pp. 2198-2202.

[16] P. Coupe, P. Hellier, C. Kervrann, C. Barillot, “Nonlocal Means-based Speckle Filtering for Ultrasound Images “, IEEE Transactions on Image Processing, Vol. 18, No. 10, 2009, pp. 2221-2229.