Focusing of Static and Moving Targets in Real Flight Conditions using SAR Technique

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Abstract— synthetic aperture radar is a very popular and widely used instrument for various remote sensing tasks. One of the most challenging problems is to obtain high-quality images in the case of unstable flight conditions. In the paper the problem of full platform motion compensation is discussed. A particular attention is given to the analysis of moving targets. Algorithm for estimation of moving target parameters is developed. Experimental results with real data are illustrated.

Keywords—synthetic aperture radar, motion compensation, autofocusing, moving targets, optical flow

I. INTRODUCTION

Synthetic aperture radar (SAR) is a great tool for a number of civil and military applications. A combination of all-weather and all-lighting operations capability and high-resolution imaging potential make this radar system a superior instrument [1]-[4].

In order to obtain a well-quality imagery, a very precise SAR platform motion compensation should be applied. This is especially crucial for radars operating on light-weight platforms and UAVs [5]-[6]. Due to the specifics of synthetic aperture construction, a precision up to fractions of wavelength should be provided on trajectory segments of several hundred meters lengths. The problem is that modern navigation systems have a limited precision, thus, often leading to some residual uncompensated platform movement. This results in strongly defocused images [6]-[7].

In the paper, we analyze two important problems. Firstly, we describe a novel trajectory reconstruction algorithm, which allows to estimate residual uncompensated deviations and refocus the SAR images of a static scene. Secondly, we demonstrate that moving target parameters can be estimated with the single-antenna SAR system.

In Section II, principles and challenges of SAR image formation are considered. Section III contains the description of proposed platform trajectory reconstruction algorithm. Developed target parameter estimation algorithm is considered in Section IV.

II. SAR IMAGE FORMATION IN REAL CONDITIONS AND TRAJECTORY RECONSTRUCTION

A. Image Formation and Motion Compensation

SAR image formation is performed as a two-dimensional compression of backscattered radar signal. Processing in range direction is commonly accomplished using linear frequency modulated or similar waveforms [4]. Azimuth signal processing or aperture synthesis is more challenging in this context. The key issue is an unstable motion of the SAR platform. Thus, in order to fully focus the SAR data, an appropriate motion compensation (MoCo) procedure should be applied [2]-[3], [6].

Considering the real and reference (ideal) trajectory of SAR platform, one can determine the slant range error to a given point on the ground plane (x_P, y_P)

$$\Delta R_E(x_P, y_P) = R_E(x_P, y_P) - R(x_P, y_P)\,, \tag{1a}$$

where R_E, R are slant ranges from the platform position on real and references trajectories, respectively. Such range migration errors and corresponding phase errors

$$\varphi_E(x_P, y_P) = -\frac{4\pi}{\lambda}\Delta R_E(x_P, y_P) \tag{1b}$$

should be properly applied to the radar data.

The most popular SAR image formation methods are so-called block-based (frame-based) algorithms [4]. In particular, the range-Doppler algorithm (RDA) is often applied. The approach performs the range-cell migration correction (RCMC) and aperture synthesis in azimuth frequency domain. Usage of fast Fourier transform (FFT) allows to use the algorithm in real-time applications.

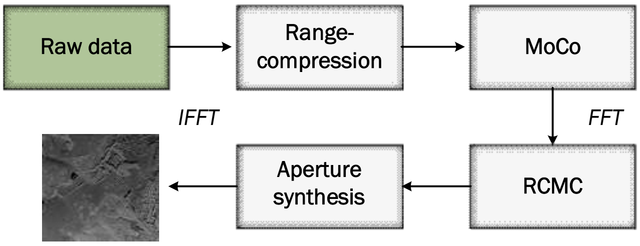

Figure 1. Main steps of SAR image formation.

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A full chain of SAR processing of a particular data frame is given in Fig. 1. Measured platform trajectory is carefully compensated in time-domain. The azimuth FFT is applied after the range-compression. At the next step, the RCMC is performed. Finally, the aperture synthesis is performed following by the IFFT [8].

In the case of high-resolution imaging, additional application of the autofocusing techniques is necessary [3], [6]-[7]. Thus, residual phase errors should be estimated directly from the SAR data.

B. *Proposed Autofocus Method*

A general idea of autofocusing is to estimate the residual trajectory deviations directly from SAR data. Recently we have proposed a concept of local-quadratic map-drift autofocus [6]. The idea was to perform a sequence of local-quadratic estimates with consequent arbitrary phase error reconstruction. The algorithm is called local-quadratic map-drift autofocus (LQMDA).

Let's consider a particular short-time interval T_S . A concept of the local map-drift is considered to estimate the Doppler rate error F_{DR}^{E} using a specifically developed estimation scheme. The first step before the local estimation is the formation of the pair of SAR images on two halves of the above considered short-time interval.

In order to reduce the number of computations, the Dechirp method [3] can be used for the SAR image formation on the short-time intervals. According to this technique, the pair of images can be obtained as follows:

$$I_1(f) = \frac{2}{T_S} \int_{-T_S/2}^{0} w_S(\tau + T_S/4) s(\tau) h^*(\tau) \exp[-2\pi i f \tau] d\tau \,, \quad (2a)$$

$$I_2(f) = \frac{2}{T_S} \int_{0}^{T_S/2} w_S(\tau - T_S/4) s(\tau) h^*(\tau) \exp[-2\pi i f \tau] d\tau \,. \quad (2b)$$

As the result, one can form the SAR image from each half-interval by using a single short Fourier transform. In the case of the presence of a local quadratic phase error, the SAR images will be defocused and shifted in the azimuth in the opposite directions [5]-[6]. The shift can be determined from the following equation:

$$\Delta f_{\max} = f_{1\max} - f_{2\max} = F_{DR}^{E} T_S / 2 \,, \quad (3)$$

where $f_{1\max}, f_{2\max}$ are maxima of corresponding synthetic patterns.

One can show that the main contribution to the Doppler rate error F_{DR}^{E} of the backscattered signal is mainly caused by the cross-track acceleration components a_Y, a_Z

$$F_{DR}^{E}(R, t_n) \approx \frac{2}{\lambda} \frac{y_R a_Y(t_n) - H a_Z(t_n)}{R} \,. \quad (4)$$

where y_R is the vertical coordinate on the Doppler centroid line, R is the slant range, H is flight altitude, λ is radar wavelength. We propose to use such range dependence for evaluation of an unknown acceleration components. For this purpose, the local estimation of Doppler rate errors should be performed within several range blocks. In this case, a series of the local estimates $\left(R_m, F_{DR}^{E}(R_m)\right)$ are obtained. Here R_m corresponds to the central range gate within the range block. Thus, it becomes possible to account the range-dependence of the phase error function.

Based on described ideas, extended version of LQMDA was proposed (Fig. 2)

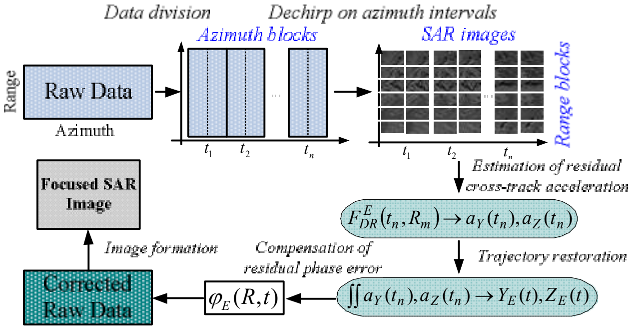

Figure 2. Main steps of LQMDA.

Firstly, the SAR data are divided on small azimuth blocks. Such blocks are processed using Dechirp algorithm resulting in a sequence of pairs of SAR images. At the next step, cross-track acceleration components are evaluated within a sequence of range blocks. After that, the residual trajectory deviations are obtained via double integration. Finally, the range-dependent residual phase error function is calculated and compensated in the SAR data.

A demo of LQMDA application is illustrated in Fig. 3.

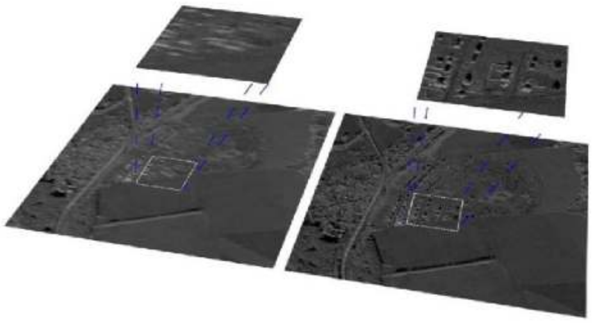

Figure 3. Demo of LQMDA application (25 looks, 2 meters resolution).

The left SAR image is obtained without autofocusing. One can observe defocused areas, which is a consequence of existence of uncompensated SAR platform deviations. Right SAR image is a result of LQMDA application. One can observe a high refinement level and well focused details. This proves the efficiency of the developed approach.

III. MOVING TARGETS ANALYSIS

In general, SAR image formation is accomplished with respect to a static scene. In the case of complete motion compensation, one can obtain a fully focused SAR image. However, a question is how to deal with moving targets. It is known that in the case of some kind of movement on a scene, moving targets appear to be shifted and defocused in resulting SAR images [9]-[10]. Moreover, in the case of multi-look processing, a smearing effect becomes crucial.

One can show [1] that using two positions (x_n, y_n), (x_m, y_m) of moving target in pairs of SAR looks it is possible to estimate the slant range to the target R_T, the absolute value of target velocity V^2 and radial velocity component of a moving target $(\vec{\mathbf{R}}_T \cdot \vec{\mathbf{V}})$

$$R_T^2 = (R_n^2 + R_m^2)/2 \,, \; \vec{\mathbf{R}}_T = (x_T, y_T, -H) \tag{5a}$$

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

$$V^2 = V_a^2 - V_a \frac{x_m - x_n}{t_m - t_n} \,, \tag{5b}$$

$$\vec{\mathbf{V}} = \vec{\mathbf{V}}_a - \vec{\mathbf{v}} = (V_a - v_x, -v_y, 0)$$

$$(\vec{\mathbf{R}}_T \cdot \vec{\mathbf{V}}) = V_a \frac{x_n t_m - x_m t_n}{t_m - t_n} \,. \tag{5c}$$

Here t_n, t_m correspond to the centers of single-look time intervals, V_a is aircraft velocity, (x_T, y_T) is a target position at the center of considered acquisition interval.

In this paper, we introduce the approach for automatic detection of moving target positions in single-look SAR images. It is proposed to integrate the optical flow (OF) technique for this purpose [12]-[13]. According to the definition, the OF is the apparent motion of the image objects between two consecutive frames (video frames in optical band) [14]. Interesting, that one can consider a pair of SAR looks in similar way.

Assuming that the pixel intensity is preserved, one can derive the OF equation

$$I_x u + I_y v + I_t = 0 \,, \tag{6}$$

where I_x, I_y are the spatial gradients of the image, $I_t = I_{iL+1} - I_{iL}$, $u = dx/dt, v = dy/dt$, $iL, iL+1$ are indexes of adjacent SAR looks. Since we have two unknown OF components (u, v), it is impossible to solve (6) for a single pixel. Therefore, according to the Lucas-Kanade method [14], the OF is considered to be the same within the local pixel neighborhood. This idea allows to construct the set of equations within the local image patch

$$\begin{bmatrix} \sum I_x^2 & \sum I_x I_y \\ \sum I_y I_x & \sum I_y^2 \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} = -\begin{bmatrix} \sum I_x I_t \\ \sum I_y I_t \end{bmatrix} . \tag{7}$$

Here the summation is performed within a specified spatial window around a given image pixel. Thus, the OF can be separately estimated for the chosen set of image pixels.

There are several difficulties arising in real conditions. At first, a pixel intensity preservation condition is not held due the speckle noise. Secondly, real antenna modulates the backscattered signals. Finally, the scattering properties of some objects are changing with viewing angles, which additionally complicates the process as well. Fig. 4 illustrates an example of SAR images pair and estimated OF values.

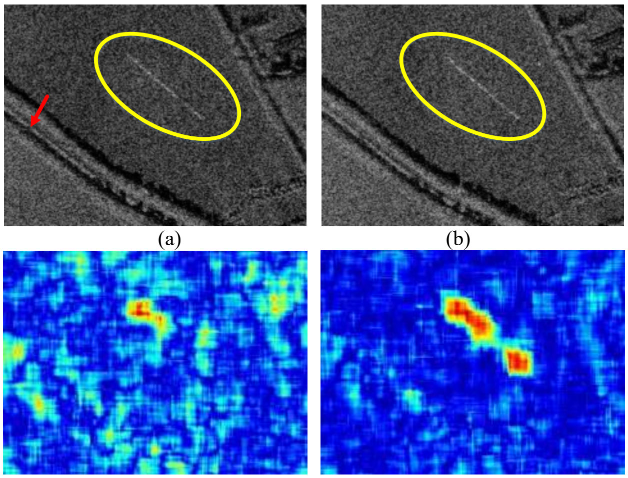
(a) (b)
(c) (d)

Figure 4. Optical flow from SAR looks pair.
(a – first SAR look, b – second SAR look,
c – optical flow before preprocessing, d – optical flow after preprocessing).

Fig. 4a and Fig. 4b are single-look images. There is railroad, but the train appears beyond it. Example of estimated OF is illustrated in Fig. 4c. One can observe a lot of false detections. In order to improve the performance, we propose to apply two important preprocessing steps. At first, the histograms of both SAR looks are adjusted according to the histogram of the multi-look image. The effect of real pattern is compensated using such step. Secondly, the speckle filtering is performed [15]. Fig. 4d contains the OF image after proposed preprocessing. One can clearly observe the trace of the moving train.

Since we consider four unknown moving target parameters, namely, velocity components v_x, v_y and position x_p, y_p, but there only 3 equations (5), there is an ambiguity “target velocity-target location” [16]. We propose to utilize the detected road segments for this purpose assuming that all considered moving targets are moving along the roads.

Based on proposed ideas, the final algorithm for extraction of moving targets parameters is illustrated in Fig. 5

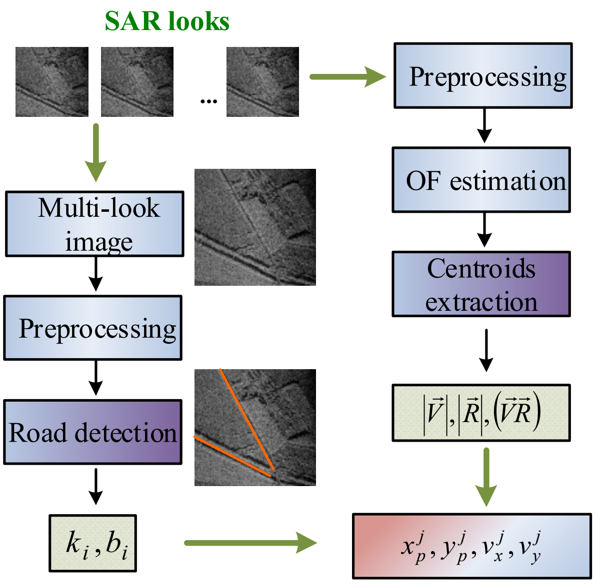

Figure 5. Framework for moving target parameters estimation.

At first, the multi-look image is formed. It is used as an input for the automatic location of road segments. At the same time, a sequence of SAR looks is used for the extraction of moving targets positions. After calculation of OF, detected target traces are analyzed and their centroid values are used as estimates for required positions. As a result, outputs are combined giving the estimate of moving target trajectory. The main advantage of the proposed scheme is a possibility to achieve the results using single-antenna SAR system.

Developed methods for SAR data focusing and moving target analysis significantly increased the efficiency of our RIAN-SAR-X system [17] produced at the Institute of Radio Astronomy.

IV. CONCLUSION

In the paper, algorithms for SAR platform trajectory and moving target parameters reconstruction were proposed. Local-quadratic phase error estimates were combined for reconstruction of residual phase error function. The phase error spatial dependence was accounted using specifically developed estimation scheme. Framework for moving target parameters extraction was proposed. Developed procedure based on optical flow led to automatic estimation of target displacements. Proposed methods were successfully tested using experimental data.

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