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Modifications of Range-Doppler Algorithm for Compensation of SAR Platform Motion Instabilities

Kriti S[1].

Department of ECE, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, India

Research Article

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***Abstract*— To address issues with SAR platform motion instabilities, two variations of the range-Doppler algorithm (RDA) have been put forward. In order to rectify radiometric inaccuracies, multi-look processing based on the RDA with an expanded Doppler bandwidth was first presented. Second, in order to apply the RDA in a newly created local-quadratic map-drift autofocus (LQMDA) approach, it has been adjusted to execute SAR image generation on short-time acquisition intervals. Using experimental data collected by aerial SAR equipment, the approaches' performance is shown.**

***Keywords*— range-Doppler algorithm (RDA), focusing, picture creation, multi-look processing, radiometric errors, and synthetic aperture radar (SAR)**

I. Introduction

One popular tool for high-resolution imaging of the earth's surface is synthetic aperture radar, or SAR [1]–[4]. Transmitting pulses with a linear frequency modulation is often used to obtain high range resolution [4]–[5]. Coherent processing of the received pulses during the SAR platform's movement yields high azimuth resolution. The primary benefits of this kind of radar are its capacity to provide high-resolution pictures with a physically compact antenna and its independence from lighting and weather.

Due to their fast operating availability and cheap exploitation costs, lightweight aircraft and unmanned aerial vehicles (UAVs) have grown more popular as SAR platforms during the last ten years [6]–[7]. The unsteady movement of the platform under actual flight circumstances is one of the current challenges in the creation of SAR images from a lightweight platform [1]–[4]. In example, the sensor's trajectory may differ much from a straight line, therefore it has to be monitored very precisely. Additionally, the antenna beam's direction may significantly alter over time. If these flight instabilities are not appropriately compensated for, the resultant SAR pictures exhibit brightness changes and defocusing effects, which deteriorate image quality [1], [8]–[9].

Thus far, many methods for analysing SAR data have been devised [1]–[4]. One of the most used algorithms is the range-Doppler algorithm (RDA) [4], [9]–[10]. The method's computational efficiency and ease of implementation are its primary merits. But the issue is that in this instance, the SAR processing is carried out on the presumption that the actual antenna orientation angles are constant, and the sensor's trajectory is measured using a

very great accuracy. In actual flying situations, the aforementioned parameters are often not met.

Two new RDA changes are presented in the study. We demonstrate that the two aforementioned issues, namely the adjustment of the unstable actual antenna beam direction and the estimate of the residual phase errors from the SAR data via autofocusing, can be effectively resolved by our SAR method.

The RDA and multi-look processing in the range-Doppler domain are explained in Section II. The concepts for using the RDA to correct radiometric inaccuracies in SAR pictures and compensate for an unstable antenna beam orientation are presented in Section III. Section IV describes the use of the specially modified RDA in a newly developed SAR focusing technique. Examples of SAR photos captured using Ku-band and X-band aerial SAR equipment demonstrate the effectiveness of the suggested methods.

II. Principles of Range-Doppler Algorithm

In this section, main principles of the SAR image formation are briefly described and peculiarities of the SAR data processing in the range-Doppler domain are considered.

A. Principles of SAR image formation

The general task of any SAR processing algorithm is to focus the SAR data [2]-[4]. This processing can be considered as a two-dimensional compression of the backscattered signals. A basic block-scheme of a typical SAR processing algorithm is shown in Fig. 1.

After the range compression of the raw data [4]-[5], the range cell migration correction (RCMC) is applied [2]-[4]. The effect of the range cell migration is related with the fact that the distance from the particular target to the moving SAR platform changes with time. As a result, the backscattered signal migrates throw the adjacent range cells during the SAR platform motion. Thus, after the range compression, the azimuth signal of the particular point target will be concentrated along a so-called migration curve. The RCMC is accomplished as the interpolation step along this migration curve [4]. The next important step of the SAR processing is the azimuth compression, which is performed as a convolution of the backscattered signal with a reference function [2]-[4]. The reference function is calculated based on the SAR platform trajectory parameters and the antenna beam orientation,

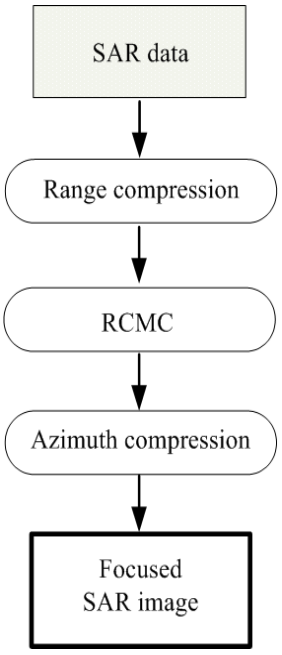
B. SAR processing in the range-Doppler domain

The key differences between the SAR processing algorithms are related with the way how the RCMC and azimuth

will be combined into the single migration curve at this range in the range-Doppler domain [4] as shown in the right figure. After some straightforward mathematical derivations [4], one can find the equation for such migration curve in the range-Doppler domain:

$$R(f) = \frac{R\sqrt{1-\frac{\lambda^2 f_{DC}^2}{4V_X^2}}}{\sqrt{1-\frac{\lambda^2 f_D^2}{4V_X^2}}}, \quad (1)$$

where R is the slant range from the antenna phase center to the target when it crosses the center line of the antenna footprint,



where Δt_{max} is a linear shift, which can be estimated via cross-

into the frequency domain. In this way, the individual target spectra will be weighted properly.

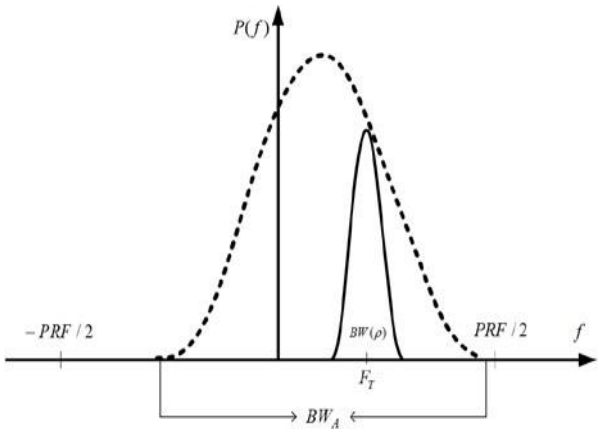


Fig. 8. SAR processing on a short-time interval in the range-Doppler domain

correlation of SAR images pair. In order to obtain the precise position of the cross-correlation peak several image preprocessing steps should be performed. In particular, local centering and normalization. This allows to enhance the contrast features and balance the contributions from different image parts. After the estimation of the cross-correlation peak position, the value of the local-quadratic phase error (13) is calculated. It should be emphasized that the proper SAR image synthesis using the modified RDA allows to perform the above described local estimation.

Second key step of the developed autofocus algorithm includes the reconstruction of an arbitrary residual phase error from the extracted local estimates. Fig.9 illustrates the overall scheme of the proposed LQMDA.

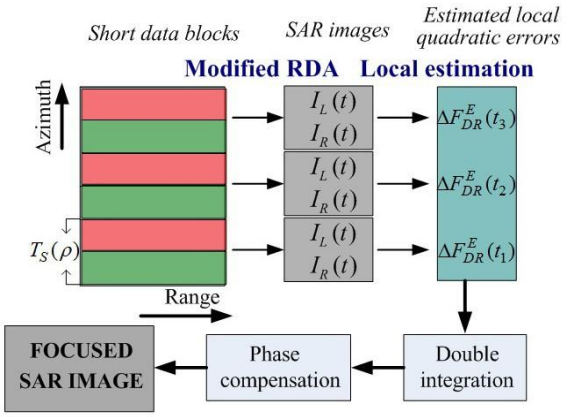


Fig. 9. Block-scheme of LQMDA

The block-scheme of the SAR processing with the incorporated LQMDA is illustrated in Fig. 8.

At first, the received raw data are compressed in range and the 1st-order (range-independent) motion compensation is applied. Then, the range cell migration correction (RCMC) is performed in the range-Doppler domain. After that, the 2nd-order (range-dependent) motion compensation is accomplished. At the next step the developed autofocus algorithm is applied for the estimation of the residual phase error function.

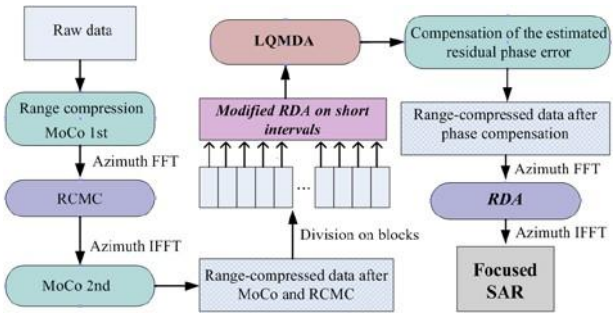


Fig. 10. Block-scheme of the SAR processing with developed autofocus method

After division of the SAR data into a sequence of the azimuth blocks the modified range-Doppler algorithm adopted for such SAR processing is applied to build the pair of SAR images. After that the linear shift between the images is measured to extract the value of the local-quadratic phase error. The local estimates on the short-time intervals provide the time-series of the local-quadratic phase errors, which is used to reconstruct the unknown residual phase error function. This function is then compensated in the SAR data and the conventional RDA is applied for the whole SAR data frame resulting in the well-focused SAR image.

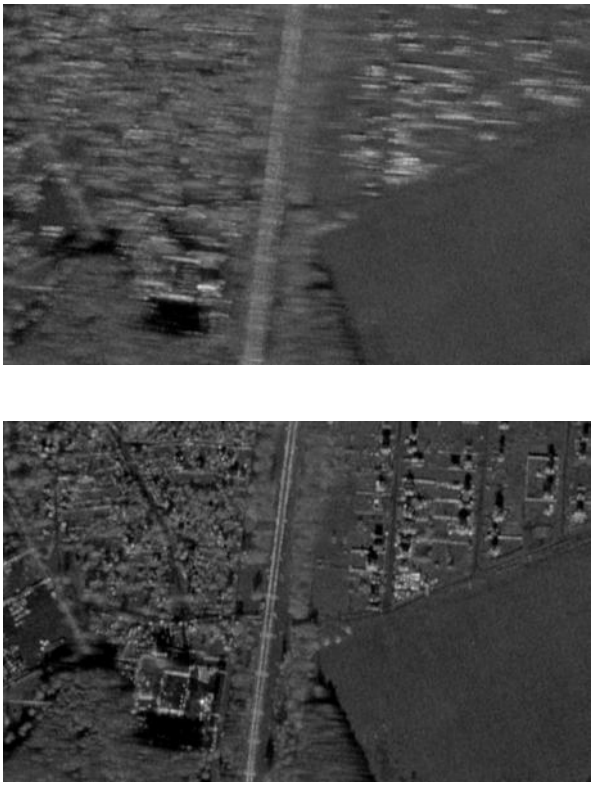
The developed autofocus algorithm has been tested on the real SAR data obtained by the X-band SAR system [7] developed at the Institute of Radio Astronomy (Ukraine).

An example of the multi-look SAR image built without autofocus is shown in Fig. 11(a). One can observe significant defocusing. The reason of such effect is the presence of an uncompensated residual phase error.

An example of the application of the developed autofocus method based on the range-Doppler processing modified for short-time intervals is illustrated in Fig. 11(b). One can see that the SAR image is well focused which proves the efficiency of the developed autofocus algorithm.

III. Conclusions

Two significant changes to the popular range-Doppler SAR processing method have been presented in this study.
First, radiometric error correction and accounting for current antenna beam fluctuations are made possible by the use of multi-look processing in the range-Doppler domain with the enlarged Doppler bandwidth. To create SAR pictures using the information gathered on the range-Doppler technique, another innovative modification



a

b

Fig. 11. Illustration of autofocusing results (a – SAR image before autofocus, b – SAR image after autofocus)

short-time intervals for the local quadratic phase error estimation, which is one of the key steps of the developed autofocus algorithm. Experimental results have shown the high efficiency of the developed methods in the combination with the modified range-Doppler algorithms.

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