Efficient Data Focusing and Trajectory Reconstruction in Airborne SAR Systems

Ievgen M. Gorovyi, Oleksandr O. Bezvesilniy and Dmytro M. Vavriv
Department of Microwave Electronics, Institute of Radio Astronomy of NAS of Ukraine
4 Chervonopraporna Str., Kharkov 61002, Ukraine
gorovoy@rian.kharkov.ua, obezv@rian.kharkov.ua, vavriv@rian.kharkov.ua

***Abstract*— formation of high-resolution SAR images from light-weight platforms is a challenging task primarily due to high instability of such platforms. Additional difficulties are related with the precision of navigation systems. In the paper the problem of residual trajectory deviations are analyzed. An efficient trajectory reconstruction method is proposed. Important practical aspects of the developed approach are discussed. Considered ideas are incorporated into the SAR processing chain. The algorithm efficiency is proven via examples of real SAR data obtained with an X-band airborne SAR system.**

Keywords—synthetic aperture radar; data focusing, phase errors; trajectory reconstruction

I. INTRODUCTION

Synthetic aperture radar (SAR) is a well-known instrument for high-resolution imaging of the Earth surface [1]-[4]. A particular interest is related with the image formation from light-weight aircrafts and UAVs due to low exploitation cost of such platforms [5]-[6]. However in this case the challenge is to ensure the proper compensation of platform motion errors which is a basis of high-quality SAR imaging. The limited precision of modern navigation systems leads to the necessity of the application of autofocusing techniques [7]-[9].

In the paper an efficient approach for the SAR platform trajectory reconstruction is described. Its main idea is related with the usage of local-quadratic phase error estimates on a sequence of short-time intervals [7]. We show how this methodology can be extended to handle the range-dependence of the phase error function. Also few important practical aspects of the developed technique are considered which allow to perform more precise and robust trajectory reconstruction. In particular, it is shown that the usage of the measured real antenna orientation angles for the SAR processing on short-time intervals can lead to the improvement of the efficiency of the autofocus algorithm. Secondly, proposed weighting scheme for the reconstruction of the cross-track acceleration components from the sequence of the local Doppler rate errors is comprehensively discussed. This gives a possibility to account the range-dependence of the residual phase error function.

We describe the main steps of the developed trajectory reconstruction method and show how the proposed methodology can be incorporated into the common SAR data focusing scheme.

In Section II, the peculiarities of SAR platform motion compensation and ideas for the residual phase error estimation are considered. Important details of the trajectory reconstruction procedure are analyzed in Section III. Real SAR data focusing examples are illustrated in Section IV.

II. MOTION COMPENSATION AND RESIDUAL PHASE ERRORS ESTIMATION

The presence of considerable motion errors is a crucial problem for light-weight platforms. Basically, the existing SAR platform deviations can be compensated via the conventional motion compensation procedure by correction of the following phase error

$$\varphi_E(x_P, y_P) = -\frac{4\pi}{\lambda}\left[R_E(x_P, y_P) - R(x_P, y_P)\right]. \quad (1)$$

Here $R_E(x_P, y_P)$, $R(x_P, y_P)$ are the ranges to the given point (x_P, y_P) on the ground from the aircraft position on the real (curved) trajectory and expected reference line respectively.

In principle, in the case of completely precise SAR platform trajectory measurement, the conventional motion compensation procedure allows to obtain a well-focused SAR image [2]-[3]. However, in the case of high-resolution imaging the limited precision of existing navigation systems may often lead to the residual uncompensated trajectory deviations. In such situations the application of autofocusing techniques becomes mandatory.

Naturally, the residual phase error has a random nature. Recently it has been shown [10] that such arbitrary phase error function can be described as a sequence of local-quadratic approximations

$$\varphi_E(R, t_n + \tau) \approx \varphi_E(R, t_n) + \varphi'_E(R, t_n)\tau + \varphi''_E(R, t_n)\tau^2 / 2, \quad (2)$$

where R is a particular range gate, t_n is the center of the considered short-time interval of duration T_S, τ is the time within the short interval, $-T_S/2 < \tau < T_S/2$. An important thing is that each term in (2) has its separate influence on resulting SAR image built on corresponding short-time interval. The linear phase term $\varphi'_E(R,t_n)\tau$ leads to the image shift in the azimuth direction, while the quadratic phase term $\varphi''_E(R,t_n)\tau^2/2$ results in defocusing effect. The constant phase term $\varphi_E(R,t_n)$ does not affect on imaging process.

It was shown [7], [11] that local-quadratic phase error $\varphi''_E(R,t_n)$ can be successfully estimated using the known map-drift principle [7]-[9]. For this purpose the pair of SAR images are formed on the considered short-time interval T_S.

Let' consider how this can be achieved. A good option for the formation of SAR images pair is Dechirp algorithm [3], [12]. According to this technique the images are formed in the following way

$$I_1(f) = \frac{2}{T_S}\int_{-T_S/2}^{0} w_S(\tau + T_S/4)s(\tau)h^*(\tau)\exp[-2\pi i f\tau]d\tau \,, \quad (3a)$$

$$I_2(f) = \frac{2}{T_S}\int_{0}^{T_S/2} w_S(\tau - T_S/4)s(\tau)h^*(\tau)\exp[-2\pi i f\tau]d\tau \,. \quad (3b)$$

Here $w_S(\tau)$ is a weighting window, $h(\tau)$ is a time-domain reference function,

$$h(\tau) = \exp[2\pi i(F_{DC}\tau + F_{DR}\tau^2/2)]\,,$$

where F_{DC} and F_{DR} are the known Doppler centroid and Doppler rate calculated from the navigation data. As a result, the accurately measured linear shift $\Delta f_{\max}$ between the images is used to determine the value of the Doppler rate error

$$F_{DR}^{E} = 2\Delta f_{\max}/T_S \,. \quad (4)$$

The linear shift $\Delta f_{\max}$ is commonly measured via the cross-correlation of SAR images pair [7].

We have shown that the sequence of the local-quadratic phase error estimates can be used for the reconstruction of the residual phase error function via double integration [7]. In the next section it is described how the developed methodology can be extended to the trajectory reconstruction which will allow to successfully handle the range-dependence of the phase error function.

III. PROPOSED TRAJECTORY RECONSTRUCTION ALGORITHM

The range-dependence of the residual phase error function complicates the problem of its estimation from the SAR data. This affects on the data focusing results especially in the case of low-altitude or wide-swath SAR systems.

In order to account the range-dependence, we propose to use the local estimates of the Doppler rate errors (4). According to the definition, the complete Doppler rate of the backscattered signal can be determined as follows

$$F_{DR}(R,t_n) = \\ = -\frac{2}{\lambda}\left[\frac{1}{R}\left(\left|\vec{V} + \vec{v}_E(t_n)\right|^2 - \left(\frac{\vec{R}\cdot\left(\vec{V} + \vec{v}_E(t_n)\right)}{R}\right)^2\right) - \frac{\vec{R}\cdot\vec{a}_E(t_n)}{R}\right], \quad (5)$$

where $\vec{v}_E(t_n)$ is the velocity error vector, $\vec{a}_E(t_n)$ is the acceleration error vector, and $\vec{R}$ is the slant range vector. It has been found that the main contribution to the phase errors comes from with the cross-track acceleration components. Thus, the estimated Doppler rate error can be written as

$$F_{DR}^{E}(R,t_n) \approx \frac{2}{\lambda}\frac{y_R a_Y(t_n) - H a_Z(t_n)}{R}\,, \quad (6)$$

where

$$y_R = -H\tan\alpha\sin\beta + \cos\beta\sqrt{R^2 - H^2 - (H\tan\alpha)^2}\,, \quad (7)$$

R is the slant range, α, β are the antenna pitch and yaw angles, respectively.

The expression (6) can be used for the estimation of the cross-track acceleration components. For this purpose, one can construct the mean square estimator (MSE) based on the Doppler rate errors extracted from the sequence of range blocks:

$$MSE(a_Y(t_n), a_Z(t_n)) = \\ = \sum_{m=1}^{M_R} w_m(t_n)\left[\frac{2}{\lambda}\frac{y_{R_m} a_Y(t_n) - H a_Z(t_n)}{R_m} - F_{DR}^{E}(R_m,t_n)\right]^2, \quad (8)$$

where R_m is the central range gate of each range block, and $F_{DR}^{E}(R_m,t_n)$ are the estimated Doppler rate errors for each range-block based on the described linear-shift measurements (4), M_R is the number of range blocks. In order to increase the efficiency, we propose to use the values of the cross-correlation functions maxima as the weighting coefficients $w_m(t_n)$.

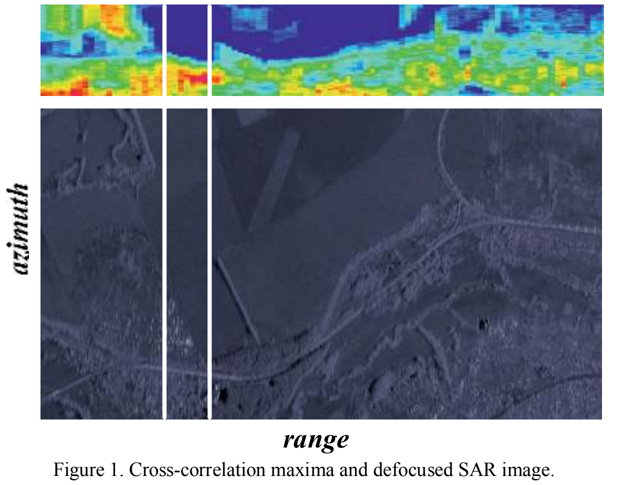


Figure 1. Cross-correlation maxima and defocused SAR image.

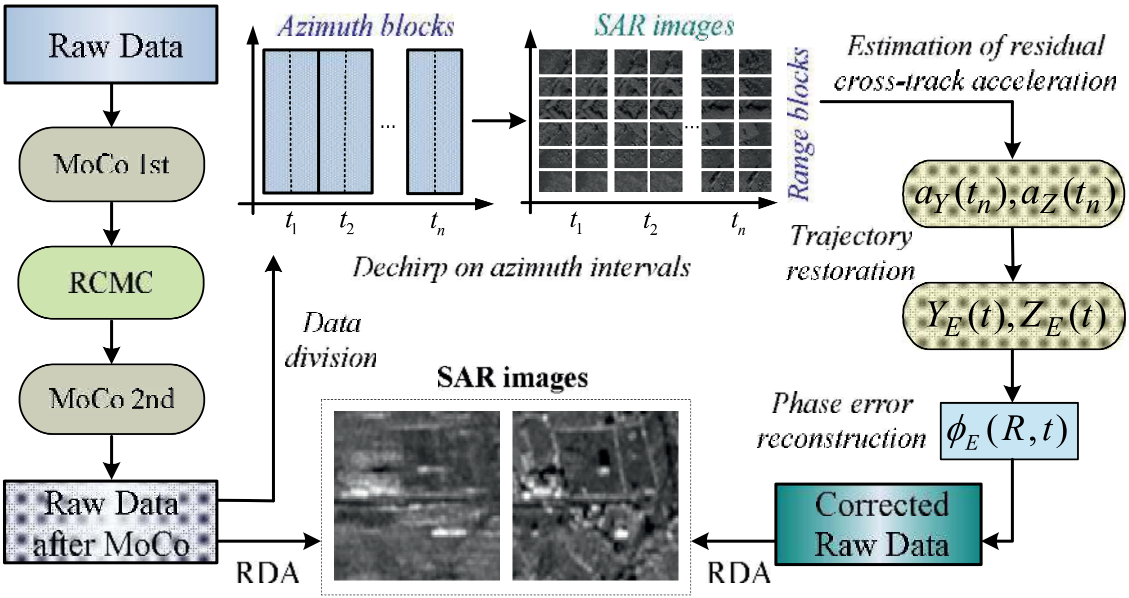


Figure 2. Block-scheme of SAR data focusing procedure.

Figure 1 contains an example of the calculated cross-correlation maxima for a sequence of azimuth short-time intervals and obtained defocused SAR image based on the existing navigation data.

One can observe that the values of the cross-correlation peaks are proportional to the image contrast. Such correspondence is apparent within the area between two vertical lines added for illustration purpose. Evidently, that the peak position estimation will be more accurate in the areas with a higher contrast. Therefore, the usage of such weighting allows to provide more reliable and precise estimates for the cross-track acceleration components.

The usage of the measured real antenna orientation angles can additionally improve the efficiency of the local Doppler error estimation. Using (6)-(7) and assuming that the average antenna orientation angles are fixed and equal to zero ($\overline{\alpha} = \overline{\beta} = 0$), one can evaluate the value of the bias of the Doppler rate error estimate

$$\Delta F_{DR}^{E}(R,t_n,\alpha,\beta) = \frac{2a_Y(t_n)}{\lambda R} * \\ * \left[H\tan\alpha\sin\beta + \sqrt{R^2 - H^2} - \cos\beta\sqrt{R^2 - \frac{H^2}{\cos^2\alpha}} \right]. \quad (9)$$

The value of this bias depends on the SAR geometry, cross-track residual acceleration component a_Y and the antenna orientation angles α, β. Such bias has important influence and should be accounted at the local phase error estimation step. As a result the consistent estimates of the cross-track acceleration components will be obtained. One should emphasize that we consider the values of the real antenna orientation angles which are used for the SAR processing on a short-time interval.

After the cross-track acceleration evaluation the trajectory deviations are retrieved via double integration. Assuming that the residual velocity errors and trajectory deviations do not have any linear trends the integration is performed as follows

$$\widetilde{V}_{Y,Z}(t) = \int_0^t a_{Y,Z}(t)dt, \quad V_{Y,Z}(t) = \widetilde{V}_{Y,Z}(t) - \left\langle \widetilde{V}_{Y,Z} \right\rangle, \quad (10a)$$

$$\widetilde{Y}_E(t) = \int_0^t V_Y(t)dt, \quad Y_E(t) = \widetilde{Y}_E(t) - \left\langle \widetilde{Y}_E \right\rangle \\ \widetilde{Z}_E(t) = \int_0^t V_Z(t)dt, \quad Z_E(t) = \widetilde{Z}_E(t) - \left\langle \widetilde{Z}_E \right\rangle . \quad (10b)$$

As a result, one can obtain the reconstructed SAR platform deviations. After that the residual range-dependent phase error can be calculated and properly compensated in the SAR data.

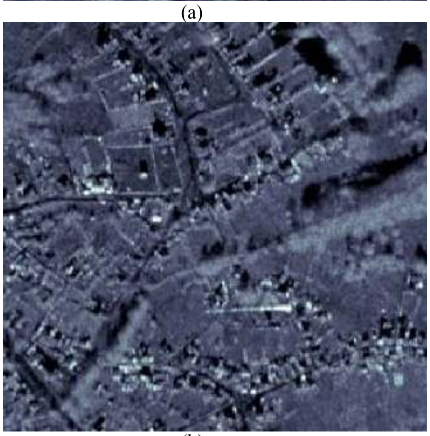
IV. Processing of Real SAR Data

This section contains the description of the whole SAR data focusing procedure. The developed trajectory reconstruction algorithm has been successfully integrated into the SAR processing chain.

Fig. 2 illustrates the block-scheme of the SAR data focusing. At first, the motion compensation (MoCo) and range-cell migration correction (RCMC) [7] steps are applied to the range-compressed raw SAR data. At this stage, the range-Doppler algorithm (RDA) can be used for the image formation, however the resulting SAR image will be defocused. The SAR data buffer after mentioned conventional SAR processing steps is ready for the application of the proposed trajectory reconstruction technique. Short azimuth data blocks are used for the formation of the pairs of SAR images on consequent short-time intervals. Then the sequence of the Doppler rate errors $F_{DR}^{E}(R_m,t_n)$ is used for the evaluation of the cross-track acceleration components $a_Y(t_n), a_Z(t_n)$ based on the developed weighting estimation scheme (8). Finally, the residual deviations (10) are reconstructed and recalculated to the range-dependent phase error function $\varphi_E(R,t)$. After the correction of this phase error the RDA can be applied to the whole SAR data block resulting in well focused image.

We have successfully tested the proposed autofocusing procedure with the real SAR data obtained by the airborne RIAN-SAR-X system [13]. This SAR system was developed and produced at the Institute of Radio Astronomy of the National Academy of Sciences of Ukraine.

(a)



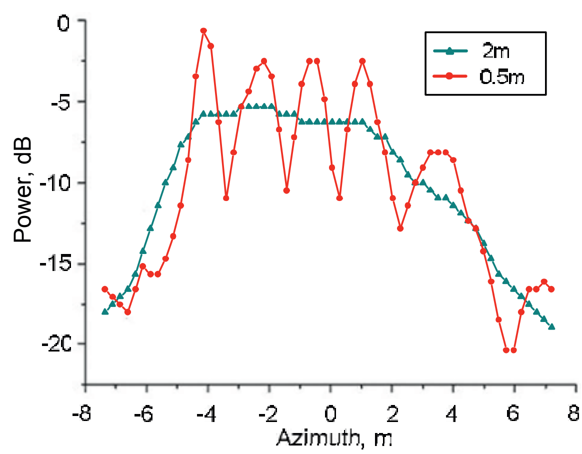
(b)

Figure 3. Multi-look SAR images (25 looks, 2-m resolution): (a) – before autofocusing, (b) – after autofocusing.

An example of multi-look SAR image obtained via the conventional SAR focusing algorithm based on the measured navigation data is shown in Fig. 3(a). Apparently, that the limited trajectory measurement precision causes the significant defocusing of the resulting image. The SAR image of the same scene after the application of the full focusing scheme including the developed trajectory restoration approach is illustrated in Fig. 3(b). This image is well focused and small details are clearly distinguished. This confirms the efficiency of the developed autofocus algorithm.

For more detailed analysis of the developed autofocus approach let's consider the following example (Fig. 4).

(a) (b)



(c)

Figure 4. Autofocus efficiency analysis: (a) – refocused image with 2 m resolution, (b) – refocused image with 0.5 m resolution, (c) – azimuth profiles.

In Fig. 4a and Fig. 4b one can see refocused (after autofocus application) SAR images with 2 m and 0.5 m resolution respectively. After comparison of azimuth profiles in Fig. 4c one can clearly see that four objects are resolved in azimuth direction for 0.5 resolution, which indicates on a high potential of the developed autofocus technique for the high-resolution SAR imaging.

V. CONCLUSION

In the paper, a novel method for the SAR platform trajectory reconstruction is proposed. It is shown how the local-quadratic phase error estimates can be used for the evaluation of the residual trajectory deviations. Important practical aspects of the developed autofocus method are considered. Examples of the real SAR data focusing prove the high efficiency of the trajectory reconstruction technique. Proposed scheme for the SAR data focusing is actively used in modern airborne SAR systems and allows to significantly improve the efficiency of such systems.

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. Goodm an, 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] V.C. Koo at al. "A New Unmanned Aerial Vehicle Synthetic Aperture Radar for Environmental Monitoring", Progress In Electromagnetics Research, Vol. 122, pp. 245-268, 2012.

[6] S. Stanko at al., "SUMATRA – A UAV based miniaturized SAR System", Proc. on 9th Synthetic Aperture Radar Conference,pp. 437-440, 2012.

[7] 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. IRS-2012, Warsaw, Poland, pp. 376-381, 2012.

[8] P. Samczynski and K. Kulpa, "Coherent MapDrift technique", IEEE Trans. on Geoscience and Remote Sensing, vol. 48, no. 3, pp. 1505–1517, March 2010.

[9] H. M. J. Cantalloube and C. E. Nahum, "Multiscale local map-drift-driven multilateration SAR autofocus using fast polar format algorithm image synthesis", IEEE Trans. on Geoscience and Remote Sensing, vol. 49, no. 10, pp. 3730–3736, Oct 2010.

[10] O.O. Bezvesilniy, I.M. Gorovyi and D.M. Vavriv, "Effects of local phase errors in multi-look SAR images", Progress In Electromagnetics Research B, Vol. 53, pp.1-24, 2013.

[11] I.M. Gorovyi, O.O. Bezvesilniy and D.M. Vavriv, "Modifications of Range-Doppler Algorithm for Compensation of SAR Platform Motion Instabilities", International Journal of Electronics and Telecommunications, Vol. 60, no. 3, pp.225-231, 2014.

[12] J. Wang, D. Cai and Y. Wen., "Comparison of matched filter and dechirp processing used in Linear Frequency Modulation", IEEE International Conference on Computing, Control and Industrial Engineering , Vol. 2, pp. 70-73, 2011.

[13] 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.