Residual Phase Errors and Autofocusing in Airborne SAR Systems

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***Abstract*—Presence of phase errors in radar data is a crucial problem for high-resolution SAR imaging. In the paper, a new idea for representation of an arbitrary phase error by its local approximations is proposed. Within such approach, a general analytical expression for the resolution degradation of multi-look SAR images is derived. The principle of local approximations is also used in a novel autofocusing approach that allows estimating and compensating of an arbitrary residual phase error function via measuring local quadratic phase errors.**

Keywords— synthetic aperture radar; residual phase errors; SAR looks; autofocusing.

I. Introduction

The formation of high-quality synthetic aperture radar (SAR) images is strictly related with the measurement of the trajectory of the SAR platform [1]-[4]. The problem is that even expensive navigation systems often do not fulfill the requirements to the measurement precision. As a result, some residual phase errors are inevitably left uncompensated in SAR data.

In the paper, a comprehensive analysis of the residual phase errors is performed. Two main problems are examined:

1) Defocusing of multi-look SAR images caused by the residual phase errors;

2) Estimation of the residual phase errors from SAR data.

In particular, in Section II, the principle of the phase error representation by local approximations is described. It is shown that an arbitrary phase error function can be effectively described via local linear phase errors (LLPE) and local quadratic phase errors (LQPE) [4]. By assuming that LLPEs and LQPEs take random values within the multi-look processing interval and by introducing particular statistical models, analytical expressions have been derived that describe the degradation of the SAR resolution of multi-look images. A comparative analysis of the SAR resolution degradation via numerical simulations and analytical formulas is performed.

The problem of the residual phase errors is commonly solved by application of autofocus techniques [5]-[8]. In Section III, the recently developed local-quadratic map-drift autofocus technique (LQMDA) [5] is described. The method is based on the local-quadratic phase errors estimation on short-time intervals with the consequent reconstruction of an arbitrary residual phase error function. The method does not require the presence of bright point scatterers on a scene and can be applied in both stripmap and spotlight modes.

The performance of the proposed autofocus method is illustrated in Section IV on radar data obtained with the airborne RIAN-SAR-X system [9].

II. Resolution of Multi-Look SAR Images in the Presence of Local Phase Errors

In general, the residual phase error presented in the SAR data can be described by an arbitrary function $\varphi(t)$. It was shown [4] that this function can be described via local approximations on short-time intervals T_S as

$$\varphi_E(t_L+\tau) \approx \varphi_E(t_L) + \varphi_E'(t_L)\tau + \varphi_E''(t_L)\tau^2/2, \qquad (1)$$

where t_n is the center of the considered short-time interval, τ is the time within the short interval, $-T_S/2 < \tau < T_S/2$. The linear phase term $\varphi_E'(t_L)\tau$ leads to a shift of the SAR image in the azimuth direction, the quadratic phase error term $\varphi_E''(t_L)\tau^2/2$ results in defocusing, and the constant term $\varphi_E(t_L)$ does not affect the aperture synthesis.

For simplicity one can determine the dimensionless local phase errors and the dimensionless Doppler rate as

$$\alpha_{EL} = \frac{1}{2\pi}\varphi_E'(t_L)T_S,\ \beta_{EL} = \frac{1}{2\pi}\varphi_E''(t_L)T_S^2,\ \beta_{DR} = F_{DR}T_S^2, \qquad (2)$$

where F_{DR} is the Doppler rate.

Let us consider the defocusing and shifting effects by analyzing the single-look and multi-look synthetic aperture patterns (SAPs). Typically, the resolution is defined as the 3-dB-level width of the main lobe of the SAP. However, in the case of significant phase errors, this definition no longer holds. In this case, an integral definition of the resolution may be used instead:

$$\rho = \frac{1}{I^{\max}}\int_{-\infty}^{\infty} I(\eta)d\eta, \qquad (3)$$

where $I^{\max}$ is the maximum value of the SAP $I(\eta)$. By using this definition, one can obtain a simple expression for the resolution of a single-look image:

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$$\rho(\beta_{EL}) = \rho_0 \frac{1 + k_W \beta_{EL}^2}{1 + \beta_{EL} / \beta_{DR}}, \quad (4)$$

where ρ_0 is the resolution that would be achieved without phase errors, β_{EL} is the LQPE on the synthetic aperture interval of the SAR look with index L, and k_W is a weighting window coefficient.

The multi-look SAR image is built by averaging of all SAR looks. The local phase errors α_{EL}, β_{EL} can be considered as random variables taking into account an arbitrary behavior of the phase error function. In order to analyze the defocusing of multi-look SAR images, one can assume for simplicity that all SAR looks are defocused by the same LQPE β_E that is a typical maximum value of the LQPEs. Also, in the case when many SAR looks are summed up, one can assume that LLPEs α_{EL} and the corresponding linear shifts η_L of SAR looks are uniformly distributed within the following intervals:

$$|\alpha_{EL}| \le \alpha_{E\max}, \quad |\eta_L(\alpha_{EL}, \beta_E)| \le \eta_{E\max}. \quad (5)$$

By using these assumptions, the multi-look SAP can be written as

$$I_{ML}(\eta, \alpha_{E\max}, \beta_E) = \frac{1}{N_L} \sum_{L=-N_L/2}^{L=N_L/2} I(\eta, \alpha_{EL}, \beta_E). \quad (6)$$

The introduced model of the uniformly distributed LLPEs and shifts (5) allows us to estimate the maximum value of the multi-look SAP as the specially averaged value of the maximum of the single-look SAP as

$$I_{ML}^{\max}(\alpha_{E\max}, \beta_E) = \max\left[\frac{1}{N_L} \sum_{n_L=-N_L/2}^{N_L/2} I(\eta, \alpha_{EL}, \beta_E)\right] \approx \approx \frac{1}{2\eta_{E\max}} \int_{-\eta_{E\max}}^{\eta_{E\max}} I(\eta, \beta_E) d\eta. \quad (7)$$

By using the developed approximation of the defocused single-look SAP [4] one can derive the analytical expression for the resolution of the multi-look SAP as a function of the local phase errors:

$$\rho_{ML}(\eta_{E\max}, \beta_E) \approx \begin{cases} \dfrac{\rho(\beta_E)}{1 - \dfrac{1}{3}\left(\dfrac{\eta_{E\max}}{(3/4)\rho(\beta_E)}\right)^2}, \\ \text{or} \quad 2\eta_{E\max} \end{cases} \quad (8)$$

where the first-line expression is used if $|\eta_{E\max}| < (3/4)\rho(\beta_E)$, and the second-line one is used otherwise. Figure 2 illustrates the comparison of the results of the numerical simulation with the proposed analytical solutions.

Figure 1(a) shows the multi-look SAR resolution as a function of the maximum LLPE $\alpha_{E\max}$ for the fixed LQPE $\beta_E = 2$. Figure 1(b) shows the resolution depending on β_E for constant $\alpha_{E\max} = 0.5$.

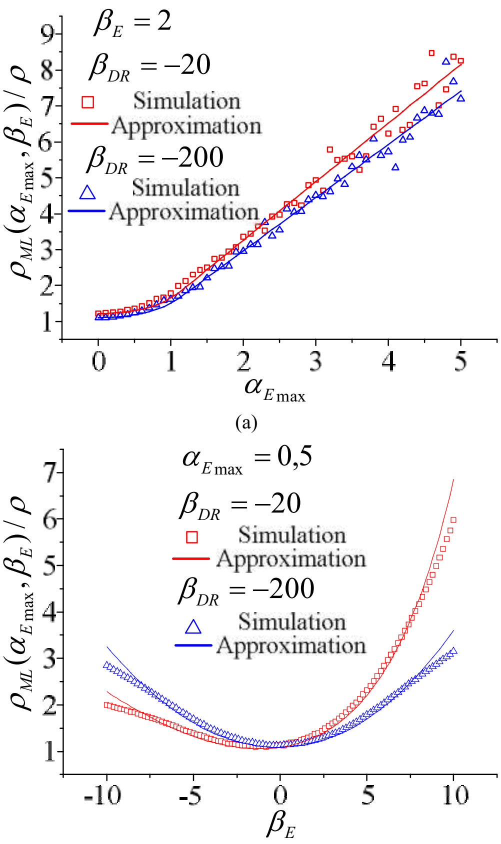


Figure 1. Resolution of the multi-look SAP as a function of local phase errors: (a) Resolution depending on LLPE, (b) Resolution depending on LQPE.

It is clearly seen that the developed analytical models demonstrate good precision. Also one should notice that for the case when the Doppler rate is small ($\beta_{DR} = -20$) the resolution degradation is significantly larger for positive values of LQPE. This result is conformed with relation (4).

III. SAR Autofocusing Based on Local Quadratic Phase Error Estimation

It is known that the requirements for the trajectory measurement precision are very high [3], which can often lead to residual uncompensated phase errors in SAR data. The common solution for the estimation and compensation of the unknown phase errors is the application of autofocusing techniques. The problem is that the existing autofocusing methods that are capable of efficient estimation of an arbitrary residual phase errors are developed mainly for the spotlight SAR mode and have many limitations when applied in the strip-map SAR mode. For instance, many nonparametric autofocus methods require the existence of bright point targets on the scene [6], while most parametric autofocus methods cannot handle arbitrary time-varying phase errors [5], [7]. An effective solution of SAR autofocusing problem is described in this paper.

Let us consider a fragment of the residual phase error function as shown in Fig. 2. One can introduce the short-time intervals and perform the local phase error approximation (1). The idea is to perform the consequent estimation of the LQPE on each interval independently. In the case of precise estimation, the LQPE will represent the value of the residual phase error second derivative $\varphi''_E(t_n)$ at the center of the short-time interval. Thus, such local estimates can be considered as a time series of the second derivative of the arbitrary residual phase error function. Therefore, an unknown residual phase error function can be reconstructed via double integration.

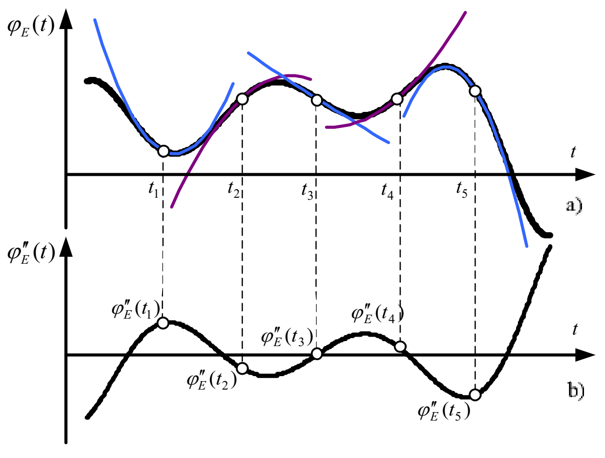


Figure 2. The residual phase error function and local approximations: (a) Phase error function, (b) Second derivative of phase error function.

The LQPE can be estimated by applying the map-drift autofocus principle on a short-time interval as follows. The described short-time interval can be divided into two parts, which are used to build a pair of SAR images. This can be done via simple convolution of a short signal with a long reference function:

$$I_L(t) = \frac{2}{T_S} \int_{-T_S/2}^{0} w_S(\tau + T_S/4) s(\tau) h^*(\tau - t) d\tau \,, \qquad (9a)$$

$$I_R(t) = \frac{2}{T_S} \int_{0}^{T_S/2} w_S(\tau - T_S/4) s(\tau) h^*(\tau - t) d\tau \,, \qquad (9b)$$

where w_S is a weighting window, $s(\tau)$ is a SAR signal and $h(t)$ is a reference function. The pair of SAR images can be formed with the range-Doppler algorithm, specifically adopted for this purpose [5], [8].

After straightforward mathematical derivations one can obtain the following approximate analytical expressions for SAR images of a point target:

$$|I_L(t)| \approx |\mathrm{sinc}[\pi\{F_{DR}(t - t_p) - \Delta F_{DR}^E (T_S/4)\}(T_S/2)]| \,, \qquad (10a)$$

$$|I_R(t)| \approx |\mathrm{sinc}[\pi\{F_{DR}(t - t_p) + \Delta F_{DR}^E (T_S/4)\}(T_S/2)]| \,, \qquad (10b)$$

where F_{DR} is Doppler rate based on trajectory measurements, ΔF_{DR}^E is a Doppler rate error to be estimated. One can show that the relative shift is determined by the LQPE as

$$\Delta t_{\max} = \frac{\Delta F_{DR}^E (T_S/2)}{F_{DR}} \,. \qquad (11)$$

Thus, the estimation of the linear shift between two SAR images in the azimuth direction gives the value of the LQPE. The common way to perform such estimation is to calculate a cross-correlation function of these two images.

The main steps of the developed autofocus algorithm are shown in Fig. 3. The whole data frame is divided on short data blocks in the azimuth direction. Each data block is split on two halves and two SAR images are formed. At the next step, the LQPE estimation is performed. Finally, the residual phase error function is retrieved via double integration. A proper compensation of the estimated phase errors in the SAR data results in a well-focused SAR image.

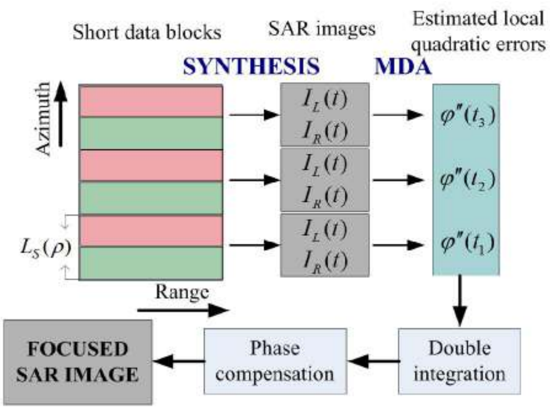
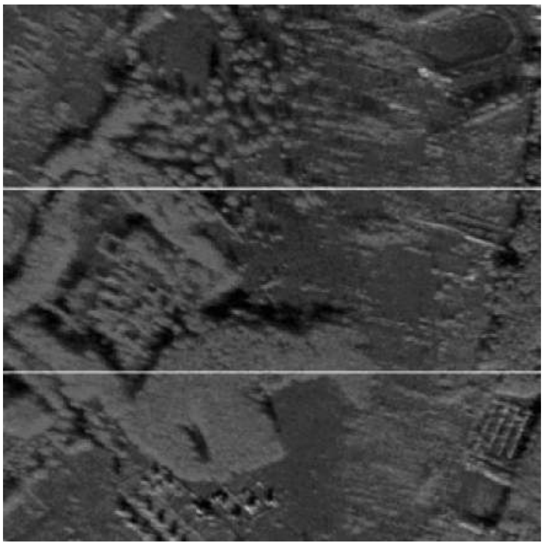


Figure 3. Simplified scheme of the local-quadratic map-drift autofocus (LQMDA).

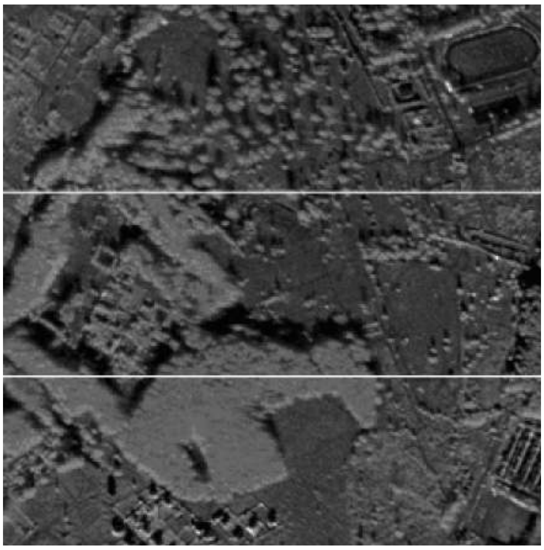
IV. Experimental Results

In this section, examples of real SAR data processing are demonstrated and discussed. The data were obtained with the airborne RIAN-SAR-X system [9] developed and produced at the Institute of Radio Astronomy of the National Academy of Sciences of Ukraine.

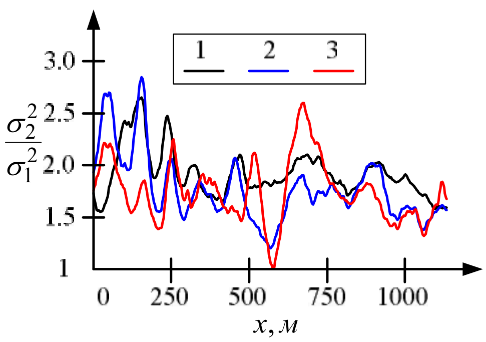
A multi-look SAR image with 25 looks and 2-m resolution built without autofocusing is shown in Fig. 4(a). One can observe significant defocusing, which is the result of the presence of residual phase errors. The multi-look SAR image after the application of the developed autofocusing approach is shown in Fig. 4(b). It is clearly seen that this image is well-focused. Figure 4(c) illustrates the relative contrast improvement, which is obtained for three horizontal image segments in Figs. 4(a) and 4(b).



(a)



(b)



(c)

Figure 4. Performance of the LQMDA approach:
(a) – SAR image before autofocusing (25 looks, 2 m resolution),
(b) – SAR image after autofocusing (25 looks, 2 m resolution),
(c) – Improvement of the contrast ratio.

The contrast values were calculated as a sample variance in consecutive sliding windows. One can observe the improvement of the contrast in average, which confirms the efficiency of the developed autofocus technique.

V. CONCLUSION

A new representation of an arbitrary phase error function via local approximations, namely the local linear and local quadratic phase errors (LLPE and LQPE), is proposed. Based on this approach and some additional reasonable assumptions about the behavior of the LLPE and LQPE, an analytical expression for the SAR resolution of multi-look SAR images as a function of local phase errors is derived. The recently developed local-quadratic map-drift autofocus (LQMDA) that is based on the LQPE estimates is also described. Examples of real SAR images confirm a high efficiency of the developed methods.

REFERENCES

[1] 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.

[2] G. Franceschetti, R. Lanari. Synthetic Aperture Radar Processing. CRC Press, 1999, 328 pages.

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

[4] 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.

[5] 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.

[6] D. E. Wahl, P. H. Eichel, D. C. Ghiglia, and C. V. Jakowatz, Jr., “Phase gradient autofocus – A robust tool for high resolution phase correction”, IEEE Trans. Aerosp. Electron. Syst., vol. 30, no. 3, pp. 827–835, 1994.

[7] 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.

[8] I. G. Cumming and F. H. Wong, Digital processing of synthetic aperture radar data: algorithms and implementation. Norwood, MA: Artech House, 2005, 625p.

[9] D. M. Vavriv at al., “SAR Systems for Light-Weight Aircrafts”, Proc. 2011 Microwaves, Radar and Remote Sensing Symp. MRRS 2011 (Kiev, Ukraine), pp. 15–19, 2011.