A Comparison of Autofocus Algorithms for SAR Imagery

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Abstract

A challenge in SAR system development involves compensation for nonlinear motion errors of the sensor platform. The uncompensated along-track motions can cause a severe loss of geometry accuracy and degrade SAR image quality. *Autofocus* techniques improve image focus by removing a large part of phase errors present after conventional motion compensation. It refers to the computer-automated error estimation and subsequent removal of the phase errors. Many autofocus algorithms have been proposed over the years, ranging from quantitative measurement of residual errors to qualitative visual comparison. However, due to the fact that different data sets and motion errors were employed, it is difficult to perform comparative studies on various algorithms. This paper compares and discusses some practical autofocus algorithms by using a common data set. Standard focal quality metrics are defined to measure how well an image is focused. Their implementation schemes and performance are evaluated in the presence of various phase errors, which include polynomial-like, high frequency sinusoidal, and random phase noise.

1. Introduction: Problem Statement

Consider a SAR system that travels along cross range, y, with its antenna pointing at slant range, r. The raw SAR signal $s(r, y)$ can be obtained by superimposing all the elementary returns from the illuminated surface:

$$s(r,y) = \iint f(r_i, y_i) g(r - r_i, y - y_i, r_i) dr_i \, dy_i \tag{1}$$

where $f(r_i,\, y_i)$ is the surface reflectivity pattern due to scatterer at $(r_i,\, y_i)$, and $g(\cdot)$ is the *impulse response* of the system (i.e., the return due to a unity point scatterer). Equation (1) represents the basic form of the *ideal* SAR raw signal in two-dimensional spatial measurement domain $(r,\, y)$. The presence of uncompensated phase errors is commonly expressed in $(k_r,\, y)$ domain:

$$s_e(k_r, y) = \iint f(r_i, y_i) e^{-jk_r r_i} g(k_r, y - y_i, r_i) e^{j\phi_e(k_r, y, r_i)} dr_i \, dy_i \tag{2}$$

where $s_e(\cdot)$ is Fourier Transform of $s(\cdot)$ in r domain (k_r denotes the spatial angular frequency of r), and $\phi_e(\cdot)$ is two-dimensional multiplicative phase errors in $(k_r,\, y)$ domain.

The SAR autofocus problem is to estimate the phase error $\phi_e(\cdot)$ based on the uncompensated SAR raw signal, and subsequently eliminate the phase error from the SAR data. Figure 1 shows the basic block diagram of a typical SAR autofocus. SAR autofocus is inherently a two-dimensional estimation problem. The fact that the phase error $\phi_e(\cdot)$ in (2) is a space-variant (target-dependent) and non-separable multiplicative noise makes SAR autofocus a challenge.

Depending on its nature and magnitude, phase errors can significantly degrade the image quality in terms of geometry linearity, resolution, image contrast, and signal-to-noise ratio (SNR). Table 1 shows two broad categories of phase errors along with the general effects of each one on SAR imagery. The classification is based on the phase error variation over the processing aperture. In general, the low-frequency phase errors affect the mainlobe of the system impulse response while high-frequency errors affect the sidelobe region. The severity of degradation varies with the magnitude and frequency of the error.

2. Some Practical Autofocus Techniques

Generally, autofocus techniques can be divided into two groups: model-based and non-parametric. Model-based autofocus techniques estimate the coefficients of an expansion that models the phase error. Elementary model-based autofocus may determine only the quadrature phase error (QPE), while more elaborate methods

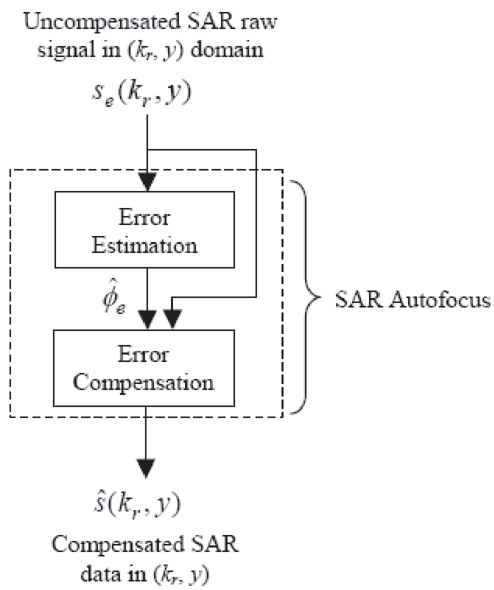


Figure 1: Block Diagram of a Typical SAR Autofocus

Table 1: Classification of Phase Errors

Phase Error Category	**Phase variation over processing aperture**	**Image Effect**
Low-frequency phase errors	Linear	Geometric displacement / distortion
	Quadratic	Image defocus, loss of resolution
	Higher-order	Distorted mainlobe, asymmetric sidelobes,
High-frequency phase errors	Sinusoidal	Spurious targets (high sidelobes)
	Wideband (Random) noise	Loss of contrast, decrease in SNR

estimate higher order polynomial-like phase errors as well. The mapdirft (MD) and multiple aperture mapdrift (MAM) are examples of model-based autofocus algorithms for low-frequency phase errors compensation [1]. The advantage of model-based autofocus is that its implementation is relatively simple and computationally efficient. However, such performance is only guaranteed if the phase error being estimated is correctly modeled. In addition, these methods are often unable to extract high frequency and wideband phase errors due to the complexity of the problem.

The second group of autofocus, commonly known as non-parametric (not model-based) autofocus, does not require explicit knowledge of the phase errors. In particular, the phase gradient autofocus (PGA) exhibits an excellent capability to remove higher order phase errors over a variety of scenes [2], [3]. Since the initial publication of PGA, several algorithms have been proposed to extend its performance. Among others, the eigenvector method (EV) is a maximum-likelihood estimator implemented within the basic structure of the PGA to replace the original phase-difference estimation kernel [4]; and the quality phase gradient autofocus (QPGA) is a strategy of choosing a pool of quality targets to provide a non-iterative PGA solution [5]. Another approach that utilizes the weighted least square (WLS) method to minimize the variance of the phase error has also been proposed [6].

The autofocus algorithms described above estimate and apply the same compensation to all targets within the entire image. Generally, space-invariant autofocus relies on averaging over many scatterers to improve algorithm performance in terms of error estimation accuracy. However, in some SAR applications, position-dependent phase errors are dominant and space-variant autofocus becomes a necessity. Space-variant effects are inherently more difficult to manage because they require a different compensation in different parts of the image. The common approach to space-variant autofocus is to break a large scene into smaller sub-images such that the error present on each sub-image is approximately invariant and hence, the conventional space-invariant autofocus procedures can be applied to each sub-image. Upon refocus, individual sub-images are reassembled or *mosaicked* together to yield the full scene focused image.

3. Proposed Performance Evaluation Standard

In order to compare and evaluate the performance of various autofocus algorithms, we propose to use two standard tests, as illustrated in Table 2. The first test examines the point target response in one-dimensional azimuth domain. The primary focal quality metrics include 3dB resolution, signal-to-noise ratio, peak sidelobe level, mean square error of phase estimation, and signal entropy. In the second test, a two-dimensional test site with 21 simulated targets is used (Figure 2). The performance evaluation criteria include image entropy [7] and Fisher information [8], as defined in the Table 2.

Table 2: Performance Test

Standard Test	**Simulated Phase Noise**	**Focal Quality Metric**
• 1D Point Target Response	• None • 5π-rad Quadratic PE • High-order PE:5π-rad Quadratic, 2π-rad Cubic, -4π-rad Quartic, and 3π-rad fifth-order PE • 0.2π-rad High-frequency Sinusoidal • Wideband random noise	• R3dB (3dB Resolution) • SNR (Signal-to-Noise Ratio) • PSL (Peak Sidelobe Level) • MSE (Mean square error) • SE (Signal Entropy)
• 2D Multiple Targets Response	• None • 5π-rad Quadratic PE • High-order PE: 5π-rad Quadratic, 2π-rad Cubic, -4π-rad Quartic, and 3π-rad fifth-order PE • 0.2π-rad High-frequency Sinusoidal • Wideband random noise	• IE (Image Entropy), $IE = -\sum\sum \lvert I_{m,n}\rvert \ln \lvert I_{m,n}\rvert$ $I_{m,n}$ is the image pixel • FI (Fisher Information) $FI = \sum\sum \lvert s_{m+1,n} - s_{m,n}\rvert^2$ $s_{m,n}$ is the target reflectivity

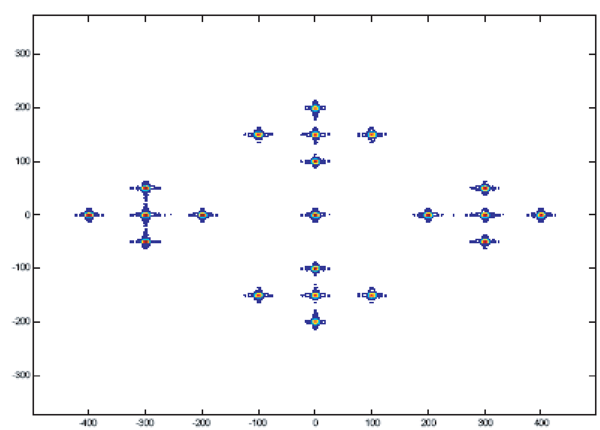
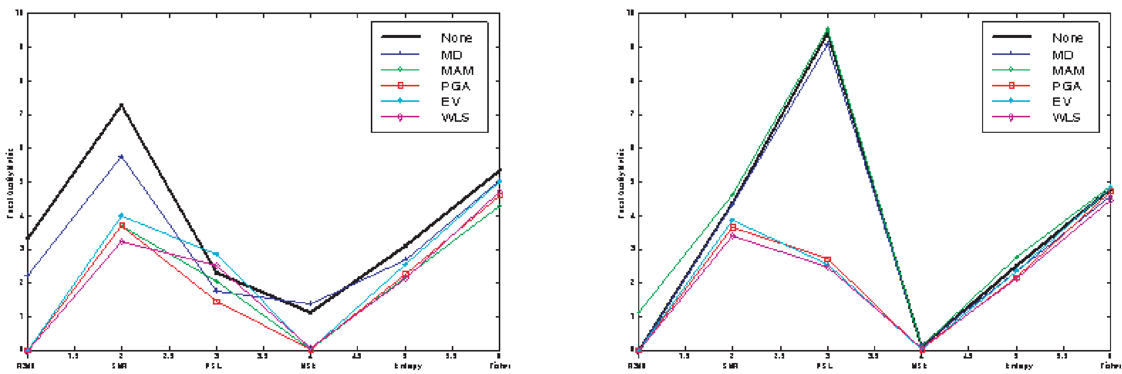


Figure 2: Standard Test Site for Evaluating Autofocus Algorithms

4. Results and Discussions

Figure 3 compares some of the practical autofocus algorithms based on their estimation capability. Model-based techniques such as MD and MAM are computational efficient for low-order phase error estimation. Non-parametric approaches such as PGA, EV, and WLS are superior for estimating a variety of phase errors. In summary, the 3dB resolution and SNR are good focal quality indicators for evaluating point target response in the presence of low-order phase errors, while the PSL criterion is best suited for high frequency phase noise estimation. The image entropy is a conventional focal indicator that measures how well an image is focused. Alternatively, the Fisher information provides similar indication about image quality with fewer computations (it can be applied directly to the target reflectivity in the frequency domain). The MSE is generally not indicative of image quality. The reason for this is that a small shift in position between estimated and actual phase errors will introduce large values of MSE. However, this shift will merely displace the target's position without affecting the image quality. All the functions described above are developed using Matlab. In order to facilitate useful comparative studies, the source codes will be offered to other researchers at no cost in near future.



(a) Polynomial–like Errors (b) High Frequency Errors

Figure 3: Comparison of Various Autofocus Algorithms

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