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Original Article

Spaceborne synthetic aperture radar (SAR) motion compensation using autofocus

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Keywords:
Chirp scaling algorithm (CSA), image quality, phase gradient autofocus (PGA), sentinel-1, synthetic aperture radar (SAR).

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Abstract
A common tool for remote sensing is Synthetic Aperture Radar (SAR). It is a very confident compared to other forms of remote sensing since it has the advantages of operating with high efficiency in all weather and throughout the day. In ideal circumstances, the SAR platform travels along a straight path at constant height and velocity. However, the eccentric orbit of satellites does not support this idea leading to decrease the quality of the focused image. This paper suggests a Phase Gradient Autofocus (PGA) solution to be applied to Sentinel-1 data addressing the SAR image-focus problem where space-variant motion defects could not be disregarded, taking the biggest advantages of using satellite SAR having access to actual data, such as Sentinel 1 level-0 and level-1 real data obtained from the European Space Agency Copernicus website, a free access hub for level-0 and level-1 data types. Furthermore, two distinct measures are employed in the endorsement process. First, measuring the contrast and entropy of the formatted image. Second, four high power reflecting points in the scene area has been visually inspected moreover assessing their amplitude response.The suggested approach that employs PGA optimizes the image quality by attaining improved entropy and contrast when compared to the original Sentinel-1 images.

1. INTRODUCTION

Quality of SAR image directly proportional with Precision of trajectory measurement of SAR platform, while it is not easy to install / implement accurate sophisticated navigation system specially on small platforms to minimize the position measurement error as it is a trade off with navigation system weight power consumption space, ventilation, etc.., that leads to motion / phase errors.

When motion errors are only estimated using extremely precise INS/GPS data, it is referred to as Motion Compensation (MoCo). Many applications, including those involving unmanned aerial vehicles[1] might not have a high-precision INS/GPS data. Such circumstances need the use of autofocus, a technique for estimating residual motion errors from raw radar data, by other words the term "autofocus" draws attention to the fact that backscattered signals are used to calculate phase errors.

We can eliminate the impacts of demodulation errors using Autofocus algorithms, regardless of the origin of the fault. Furthermore, focusing approaches minimize the high hardware expenses linked to extremely precise navigation systems. Therefore, it is practically required to combine good MoCo/autofocus with traditional imaging techniques in order to increase the quality of the image focusing. Autofocus approach selection is customarily a trade-off between the required image quality and SAR processing speed.

For SAR imaging, PGA is a particularly successful autofocus technique. This technique uses a complex image as an input rather than any parameters (Non-Parametric technique). To enhance the focusing impact of the image, the phase error is determined using the dominating scatters in the image (often the isolated strong scattering point) and adjusted by defocusing the dominant scatters. PGA has been utilized extensively in SAR imaging processing and is extremely effective for high-frequency phase error compensation[2-6]. When PGA is used, the phase error is thought to be spatially invariant. Even if the inertial information is employed for main and secondary motion compensations in real image processing, the residual motion error may also be space-variant. The motion error defects will be easier to realize in real-time imaging, which is constrained by computing power[5]. If there aren't many dominant scatters, the phase error estimation's precision is insufficient, and the PGA impact is not particularly noticeable. If there are no prominent scatters in the image, the phase error estimation may be ineffective and lead to further image defocusing.

In order to estimate phase error, PGA must identify isolated strong scattering spots (dominant scatters) in the image. The window function is then used to identify the dominant scatters in order to increase the signal-to-noise ratio.

The scheme and algorithm are accomplished using MATLAB 2020b on workstation i7-6820HQ, 32 GByte RAM instead of Sentinel-1 ground station reaching well entropy and contrastfor a scene area80 Km * 200 Km in Netherland centered at Latitude 52.9888° , Longitude 06.0432°.

II. PROPOSED WORK

A. Pre- processing

Three processes make up the pre-processing of SAR data. Analysis of the raw data comes first, followed by the extraction of Sentinel-1 factual parameters such PRF, range, and pulse width. Thirdly, the effective sensor velocity and space packet data reception time are precisely calculated.

Through these three steps and as a part of the pre-processing stage, the essential parameters were really acquired from the raw data and combined with the Chirp Scaling Algorithm (CSA) to create a focused image[7,8]. One of the most important factors impacting the outcome of the SAR image is effective sensor velocity, effective velocity can be determined by taking the SAR sensor's rectilinear geometry into account.

$$V_E = \sqrt{V_{sat} * V_{gnd}} \qquad (1)$$

WhereV_{gnd} and V_{sat} represent the ground footprint and satellite velocity, respectively, these velocities vary in accordance to orbit position and range as the magnitude of the Earth's tangential velocity changes with latitude and its direction relative to the satellite velocity vector. Thus, VE changes with time and range and must be updated with each time stamp[6].

Chirp Scaling Algorithm

The selection of SAR image generation methods is based on application or system characteristics. Execution times, power efficiency, and image quality must all be taken into account while choosing a strategy[9,10]. Since hardware devices can supply the energy required for GPU or other multi-core systems, they are a good substitute for on-board systems. But when speed and performance are the most crucial factors and power efficiency is unimportant, GPU devices are fantastic choices[11].

In actuality, CSA was created for stripmap SAR in order to dispense the interpolator used by the range cell migration correction Range Cell Migration Correction (RCMC) in Range Doppler Algorithm (RDA); it can also withstand larger squints. In order to execute RCMC shifts utilizing phase multiplies instead of interpolation, the chirp scaling process is dependent on the use of chirps[6]. Time-consuming interpolation calculation method is the biggest barrier to use the RDA in small labs with limited hardware resources. Instead, employing CSA to produce a high quality image with fewer steps, less time, less resource usage, and simpler system implementation than RDA was able to tackle this problem[6-9].

Range and Azimuth Compression (Hamming Window)

Hamming window is a type of window function used in signal processing, specifically in Fourier analysis. It is commonly used in Spectral analysis, filter design, and digital signal processing.

A window function is a mathematical function used to shape the spectrum of a signal. The Hamming window is a type of window function that provides a smooth roll-off at the edges, reducing spectral leakage and sidelobes.

The mathematical representation of the Hamming window is given by:

$$w(n) = 0.54 - 0.46 * \cos(2 * pi * n / (N-1)) \qquad (2)$$

Where: n = sample number n=1: N+1, N = number of samples

Meanwhile, a modified parameter-optimized equation was used to reduce the sidelobe level in range direction [6,12] according to what was obtained from accurate real data from Sentinel-1 as follows:

$$w(n) = 0.75 – (1-0.75) * \cos(2 * pi * n / (N-1)) \qquad (3)$$

The Hamming window has numerous advantages compared to other types of window functions, including:

- Provides good frequency resolution, making it useful for spectral analysis.
- Low sidelobes reducing spectral leakage and making it useful for filter design.
- Easy to implement making it a popular choice for digital signal processing applications.

Range Cell Migration Correction

Range Cell Migration (RCM) occurs when a target moves, smearing the received signal across several range cells and making it challenging to pinpoint the target as it trails a hyperbolic trend in azimuth direction. RCM confounds and complicates the processing, but ironically, it is a basic feature of SAR, as shown in figure.1 RCM presented after range compression and have to be processed before azimuth compression.

By adding a phase shift to the received signal, the Range Cell Migration Correction signal processing method aligns the range cells with the actual location of the target to correct for this distortion. RCMC normally executed in patch-wise means[4].

Phase Gradient Autofocus

The PGA is accredited as a formidable algorithm, non-parametric method that qualifies accurate estimator and compensator for the higher-order phase errors. The method is based on redundant measurements that are available as well as the fact that the data collected from the entire aperture and the complex image compose a pair of Fourier transformations. The Fourier transform's derivative property is used to determine the peak amplitude function within each azimuth spanning all of the compressed range bins and compute its first derivative to estimate the whole phase error function. The integration of the phase gradient yields an approximation of the phase error function. The phase estimations are then averaged over a large number of range bins using weighted least-squares[4,10].

These errors are fixed by autofocus by first determining the error that is present in the image. These issues are easily resolved by multiplying each row vector by the azimuthal frequency domain estimated vector's negative inverse using a one-dimensional Fourier transform. If the approximate phase component for each image pixel in the focusing process is correct. For roughing out the phase errors in complete SAR images[10,12].

In an iterative process, the Fourier transform and second-order statistics of azimuth data use the assumption that all of the sub-phase aperture's errors are space-invariant. They are often exclusively used in relation to one-dimensional phase errors because azimuth phase errors are the main source of SAR error especially in satellite SAR. Undeniably, same technique applied also to range phase errors[2].

While the phase error varies with azimuth, it remains constant for each azimuth point regardless of range location.

Although PGA does not attempt to fit the estimate into a polynomial model, its ability to accurately estimate the phase error vector does depend on the polynomial complexity of the vector. This is due to the fact that the more complex a phase error vector is, the more it smears the point targets in the image, and thus the more precise the length of the PGA capture window needs to be.

From real SAR image processing assessments, we conclude that the proposed method can provide better performance than several existing autofocus methods in terms of the estimation accuracy and computation time, and PGA, the industry standard for autofocus algorithms, is a very reliable method[8,13].

Processes II (A-E) are illustrated in figure.1 with all necessary domain conversions. Where AzT Azimuth time domain, AzF Azimuth frequency domain, RaT Range time domain, and RaF Range frequency domain.

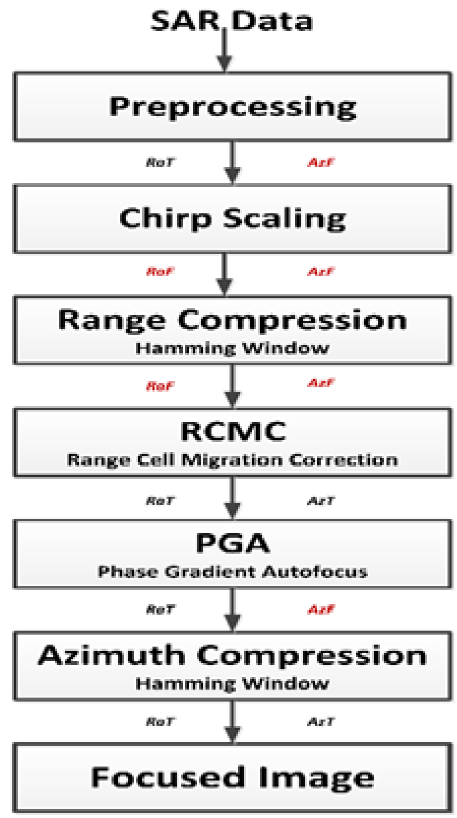


Fig. 1: Proposed CSA Image Formation with Autofocus Algorithm

III. IMAGE QUALITY METRICS and RESULTS

It is typical to visually analyze the image after focus in order to gauge how well the PGA performs in practical settings. Blur makes it difficult to see features clearly, which is a goodsign that the PGA's phase error estimate is not accurate. Surely, the appropriateness of an estimate depends on the application.

Conceptually it is hard to precisely determine the phase error as the phase error is unknown in real-world applications moreover using a single metric to verify whether the phase error estimate provided by PGA is accurate or the image is badly focused is impracticable[6,8].

In the context of SAR image processing, the PGA and entropy relationship can be interpreted as PGA enhances the focus of SAR images by correcting phase errors in the SAR signal. By improving the focus, PGA boosts the information content in the SAR image and minimize the randomness level in the image. A better entropy in the SAR image resulting from the decrease in randomness and rise in information content, indicating an improvement in the image's quality.

First, the entropy of an image is represented by[13,14]

$$\text{Entropy} = -\sum_{m}\sum_{n}\left(\frac{T^2(m,n)}{E_t}\right)\ln\left(\frac{T^2(m,n)}{E_t}\right) \quad (4)$$

Where E_t is defined as the total energy.

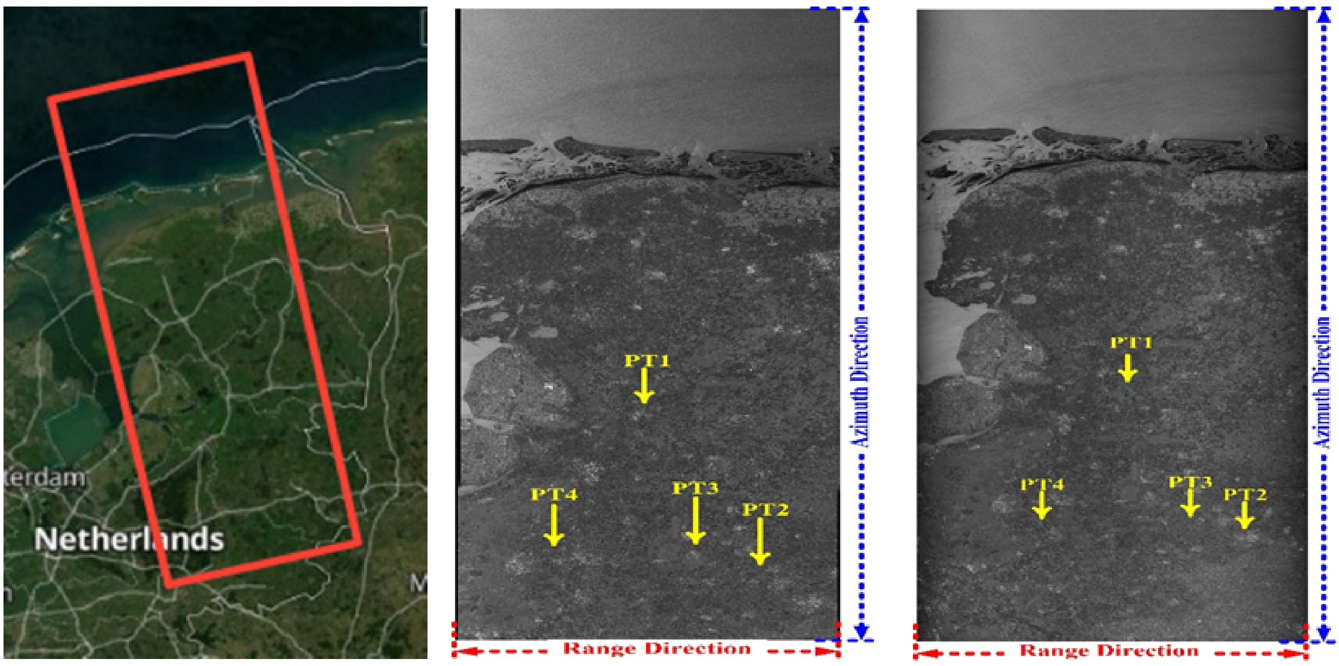
$$E_t = -\sum_{m}\sum_{n} T^2(m,n) \quad (5)$$

Second, the contrast of an image is computed as:

$$\text{Contrast} = \frac{\sqrt{G\{[T^2(m,n) - G\{T^2(m,n)\}]^2\}}}{G\{T^2(m,n)\}} \quad (6)$$

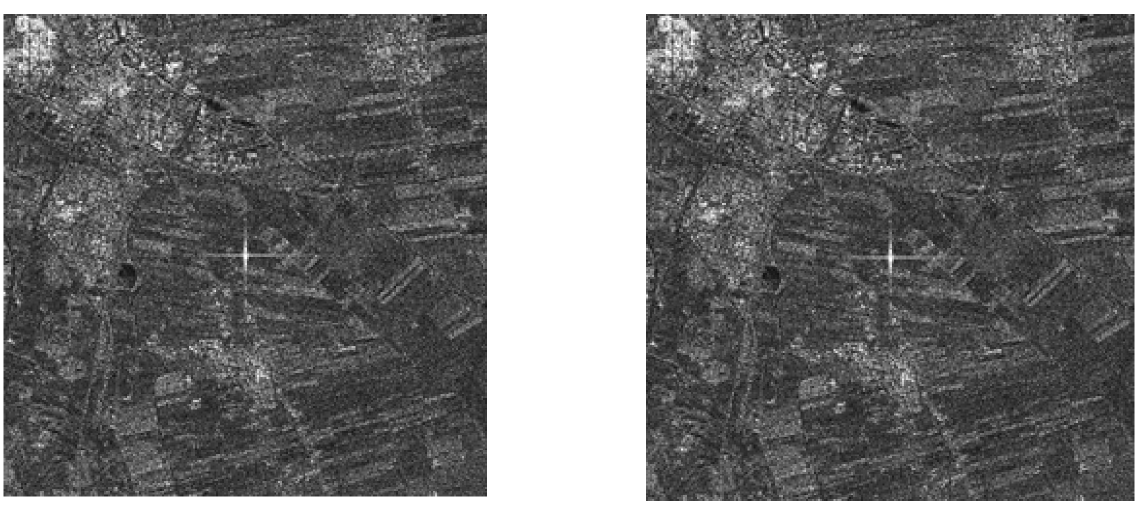
T (m,n) is the pixel intensity m=1, M, n=1, N, and G [●] is the arithmetic mean of the samples where:

$$G\{T^2(m,n)\} = \frac{1}{MN}\sum_{m=1}^{M}\sum_{n=1}^{N} T^2(m,n) \quad (7)$$



(a) (b) (c)

Fig. 2: (a) Scene area – (b) Sentinel-1 Focused Image – (c) Proposed Algorithm Focused Image



(a) (b)

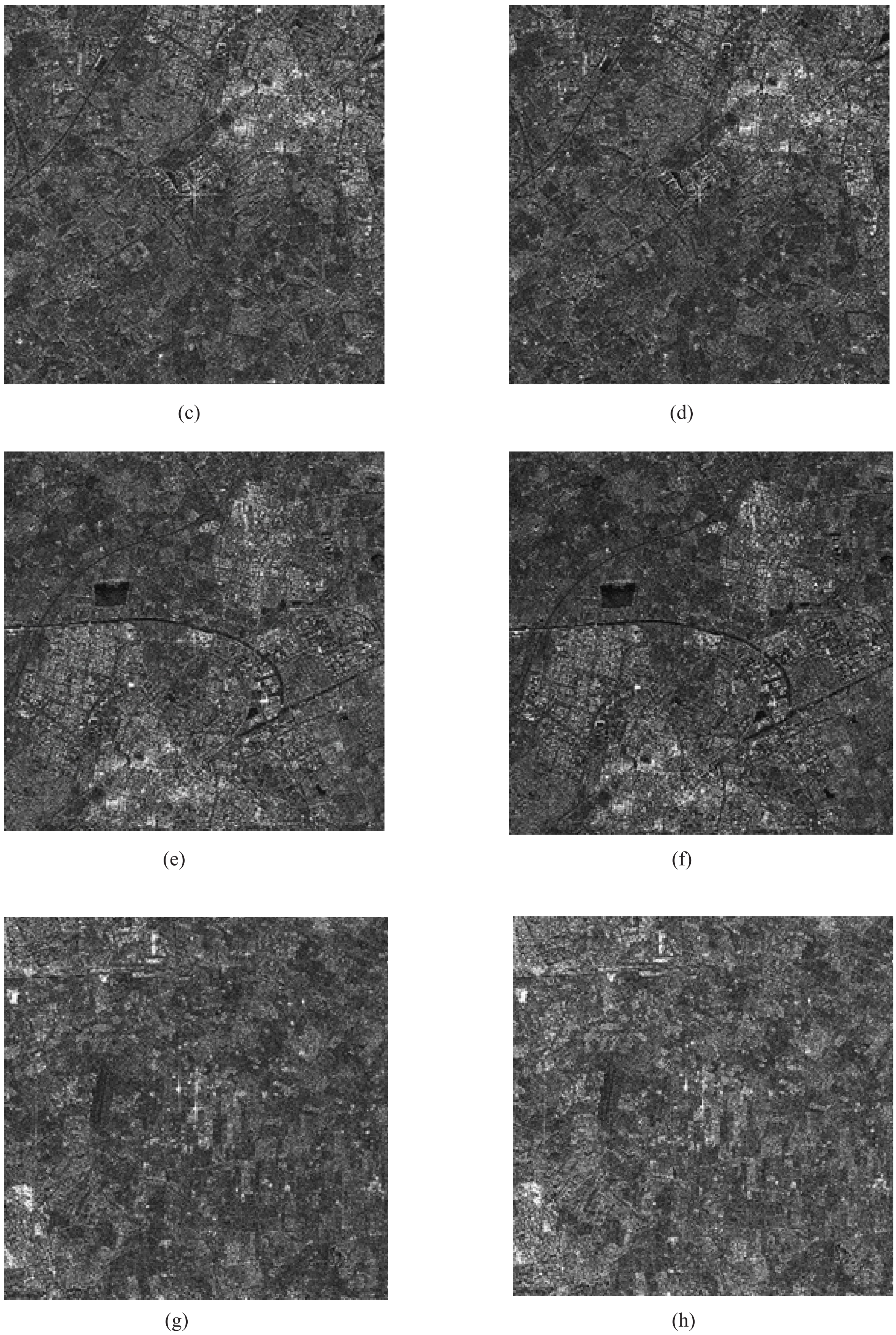


Fig. 3: Sentinel-1vs Proposed algorithm images(a) PT1 Sentinel, (b) PT1Prop. Alg. – (c) PT2 Sentinel, (d) PT2 Prop Alg. – (e) PT3Sentinel, (f) PT3 Prop Alg.– (g) PT4 Sentinel, and (h) PT4 Prop Alg.

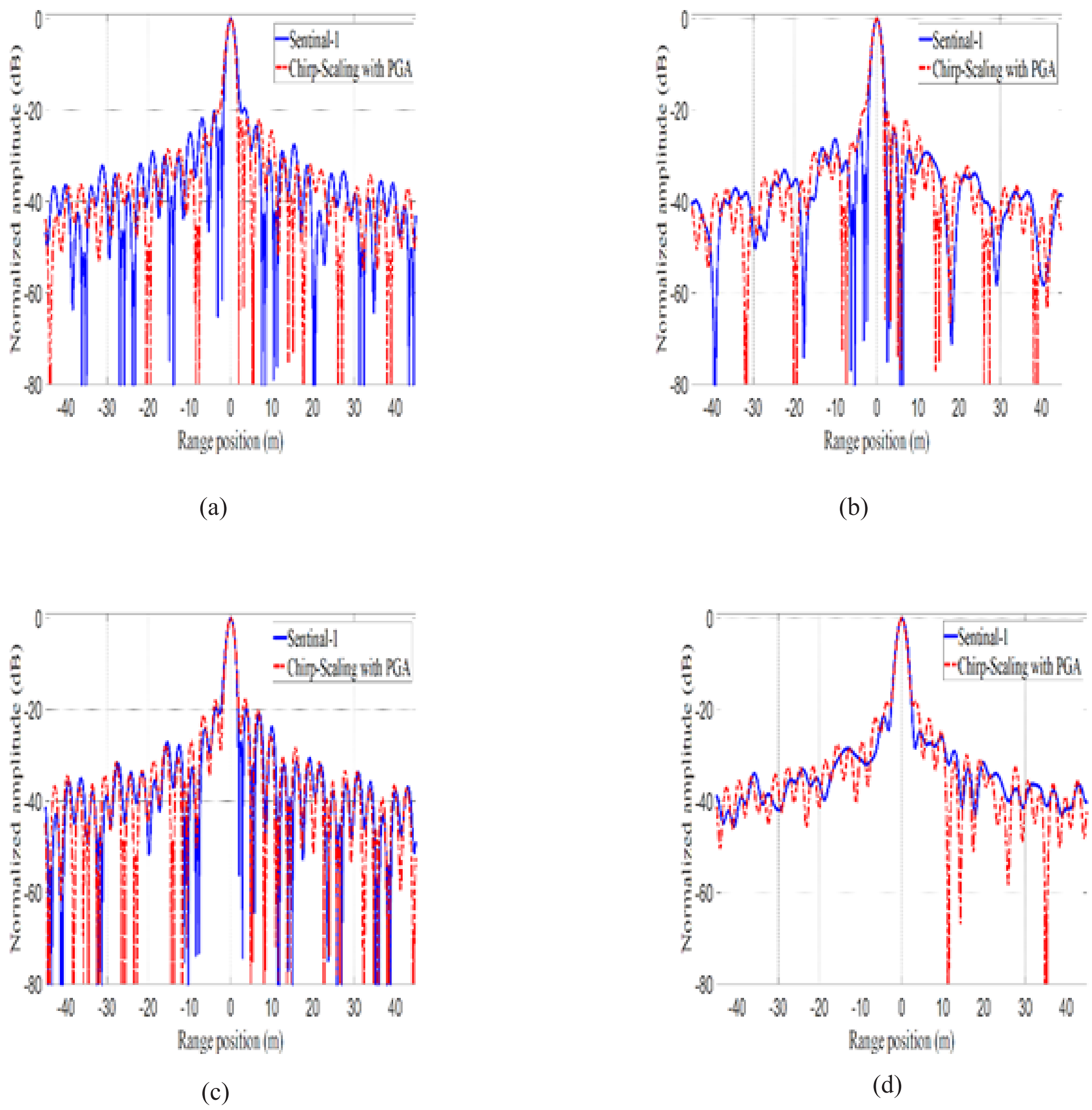
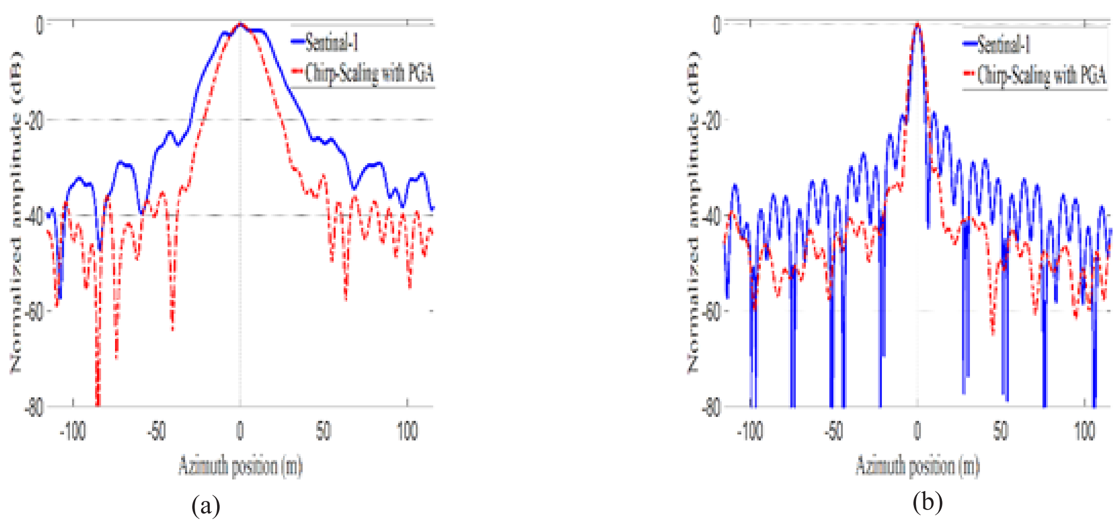
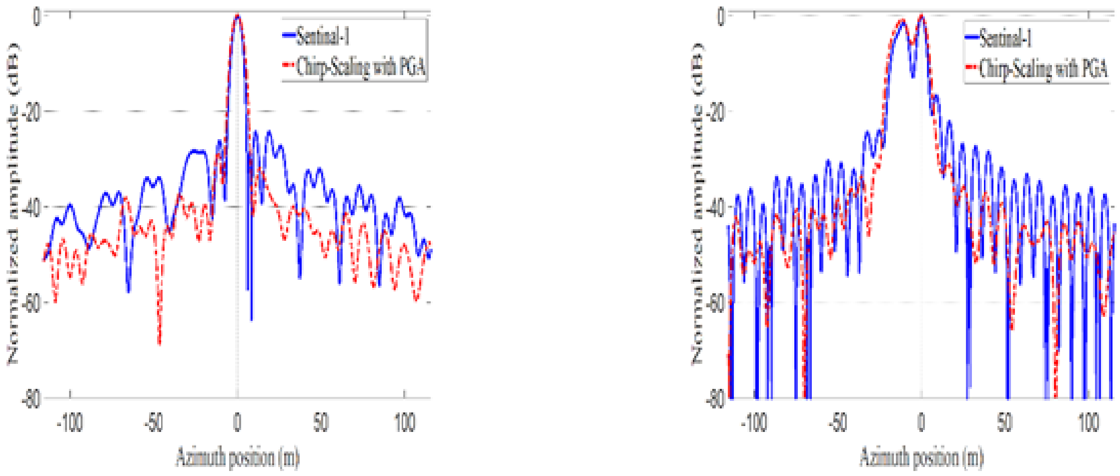


Fig. 4: Four High PowerReflecting Points Amplitude Response in Range Direction (a)PT1, (b) PT2, (c) PT3, and (d) PT4.





(c) (d)

Fig. 5: Four High Power Reflecting Points Amplitude Response in Azimuth(a)PT1, (b) PT2, (c) PT3, and (d) PT4

Table 1: Entropy and contrast for sentinel against proposed algorithm

	Sentinel-1						Proposed Algorithm "Hamming window + PGA"					
	Entropy	Contrast	PSLR	ISLR	PSLR	ISLR	Entropy	Contrast	PSLR	ISLR	PSLR	ISLR
	Ratio (unitless)	Ratio (unitless)	Range Direction (dB)		Azimuth Direction (dB)		Ratio (unitless)	Ratio (unitless)	Range Direction (dB		Azimuth Direction (dB)	
Point #1	10.151	68.191	-19.614	-14.626	-1.298	1.950	9.942	209.290	-20.084	-15.427	-30.438	-29.193
Point #2	11.804	117.268	-34.275	-17.949	-18.640	-14.266	11.755	120.634	-20.543	-17.034	-30.418	-26.935
Point #3	12.126	52.835	-19.608	-14.610	-26.255	-17.630	12.118	53.301	-28.756	-25.845	-17.961	-13.539
Point #4	12.098	51.412	-21.444	-16.091	-1.557	0.686	12.058	52.139	-18.243	-13.594	-0.866	0.769

IV. DISCUSSION

We can state with clarity and assurance after carefully examining the results presented in the table, figures, and images that all criteria for evaluating image quality have been met through visual comparison, which demonstrates the striking similarity between the images formed using the proposed algorithm and those created by the Sentinel-1 satellite.Even when employing various measuring techniques, which revealed a reduction in entropy values across all images and an increase in the contrast coefficient Also, the range and azimuth amplitude responses, represented by PSLR and ISLR which typically demonstrated a shrinking of the mainlobe as well as a reduction in the level of the sidelobes, supported these results.

It also clearly shows that the significant increase in the value of contrast for point 1 compatible with expectations as that point is in the middle of the scene area used as a reference point for the MoCo[6,12] process and has the highest reflectivity.

V. CONCLOUSION AND FUTURE WORK

Entropy is used as the objective function for this non-parametric autofocus approach. An associated windowing and chirp scaling strategy has also been presented. This method has been demonstrated to be capable of handling phase compensation resulting from residual motion inaccuracy in the Sentinel-1 SAR real data experiment.
Although the presented PGA performs and converges sufficiently for this research, there are still several areas that can be improved, such as feature selection and figuring out the threshold for each iteration. The scene would dictate these variables. The performance and convergence of the suggested algorithm would therefore be improved by modifications made using adaptive approaches, which constitute future work.

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