Synthetic Aperture Radar (SAR) Autofocus Techniques

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Due to severe phase errors resulting from the unmanned aerial vehicle used in the Blue Team's capstone project, the industry-standard phase gradient autofocus technique is not applicable. The Blue Team explored an alternative algorithm, gradient descent entropy-minimization, with preliminary but promising results.

Introduction

Radar can be used to resolve both range and motion metrics for distant objects. This facilitates many applications from speed monitoring to air traffic control to navigation with poor visibility (Ager, 2013). Typical radar systems, while providing excellent range resolution, suffer from extremely poor *azimuth* or cross-range resolution. Resolution in the azimuth is the product of beamwidth (β) and distance. As beamwidth is inversely proportional to antenna width ($\beta = \frac{\lambda}{w}$), this resolution can be improved by increasing the size of the antenna. In many applications, and in the early days of radar, constructing such antennas was not technically feasible. Synthetic aperture radar (SAR) was developed to combat this problem (Ager, 2013). A SAR system simulates a much larger antenna or aperture by collecting many radar pulses in sequence but analyzing them to form a singular image.

In a typical image, pixels are mapped to a single value: brightness. SAR image formation creates a complex image where each pixel maps to a pair: amplitude and phase. *Amplitude* corresponds to brightness in the final image; however, *phase* is used in the post processing algorithms to transform it into a viewable image.

SAR images benefit from two key properties. Radar (1) provides its own illumination, and (2) can penetrate foliage, smoke and other obstacles. These combine to provide useful applications. These include imaging scenes obfuscated by fog, cloud cover or darkness. SAR also is used to measure ocean currents and eddies (Ager, 2013). These applications generally involved satellite- or aircraft-mounted SAR systems that form extremely long apertures. A niche application, and the impetus for this research, is an unmanned aerial vehicle (UAV) SAR system. By using a UAV, one can gather information about natural disasters, such as forest fires, without risking human lives. Further, data collection can be automated. Unfortunately, unlike traditional SAR systems, UAVs are limited. Foremost, payload weight constraints place an upper bound on flight time due to power considerations. Critically, however, inertial motion compensation systems' performance is degraded on such unstable platforms. As discussed, SAR image resolution depends heavily on aperture width but image quality is also strongly correlated to positional data accuracy. Small deviations can result in blurring of the SAR image. This note summarizes the cause of these errors and targets so-called autofocus techniques to reduce the impact of poor data. It contributes an optimized gradient descent autofocus technique to minimize image *entropy*, a measure of the blur in an image.

Background

There are a variety of techniques to perform SAR image formation that fall into two large categories (Yegulalp, 1999). A common technique is to borrow a mathematical transformation from signal processing theory known as the Fourier transform. Using an optimized form of the equation, known as the fast-Fourier transform (FFT), this method relies on geometric approximations and assumptions to form the resulting image. Backprojection, a different technique,

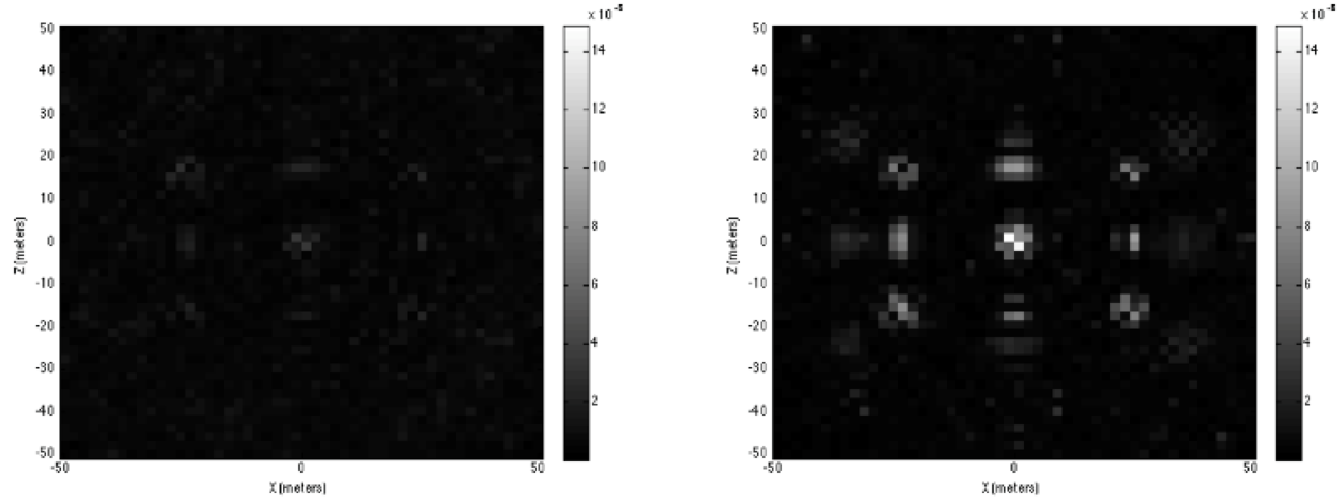

Figure 1. Left: Unfocused, noisy image. Right: Focused result.

relies on various mathematical techniques to each pixel. While geometrically exact, backprojection is more computationally intense. In spite of this theoretical perfection, however, all SAR modalities suffer from errors due to a myriad of technical factors. Positional errors due to inaccurate GPS signals, uncompensated motion errors of the antenna, Doppler effects, and other propagation errors plague the pulse history data. These errors cause blurring in resulting image. To minimize the impact of such errors, the image is autofocused. Figure 1 shows the results of such focusing.

Phase Gradient Autofocus

In 1989, Eichel, Ghiglia and Jakowatz developed phase gradient autofocus (PGA): the “gold-standard” for SAR imagery autofocus (Kragh, 2009; Eichel et al., 1989). By providing “near diffraction-limited performance” on a variety of scene contents, PGA is considered to be robust and efficient (Wahl et al., 1994). Essentially, PGA attempts to estimate the error in the current image, reduce this error, and iterate. The process executes efficiently by making strong assumptions about the SAR data such as the need for a very large aperture (Ash, 2012). Of course, for our application, which uses relatively small apertures, this technique is not suitable.

Entropy Minimization Autofocus

Working around these constraints requires a different approach: so-called “metric-based” autofocus. Entropy is an information theoretic property of a data. In our case, it roughly corresponds to the distribution of intensity in the image. That is, concentrated, bright points exhibit lower entropy than their diffuse counterparts. By minimizing entropy, we essentially “focus” the image to the human eye. Metric-based methods such as the technique discussed below have been shown to provide superior restoration abilities when compared to PGA in specific cases (Morrison et al., 2007).

Metric-based autofocus algorithms attempt to optimize an image over some measure. We seek to decrease blurriness and so we minimize entropy. Entropy (denoted by H in Eq. 1) is given by a summation of the amplitudes of the pixels in the image, where z_n is the nth pixel in the image $\boldsymbol{z}$ and E is the total energy in the image:

$$H = \frac{1}{E}\Sigma|z_n|^2 \ln|z_n|^2 \quad (1)$$

Finding the value for z that minimizes H is difficult in closed form, and so instead we employ an algorithm called *gradient descent* that iteratively approaches the answer. The technique involves computing a mathematical property of functions known as the gradient which “points” in the direction of steepest

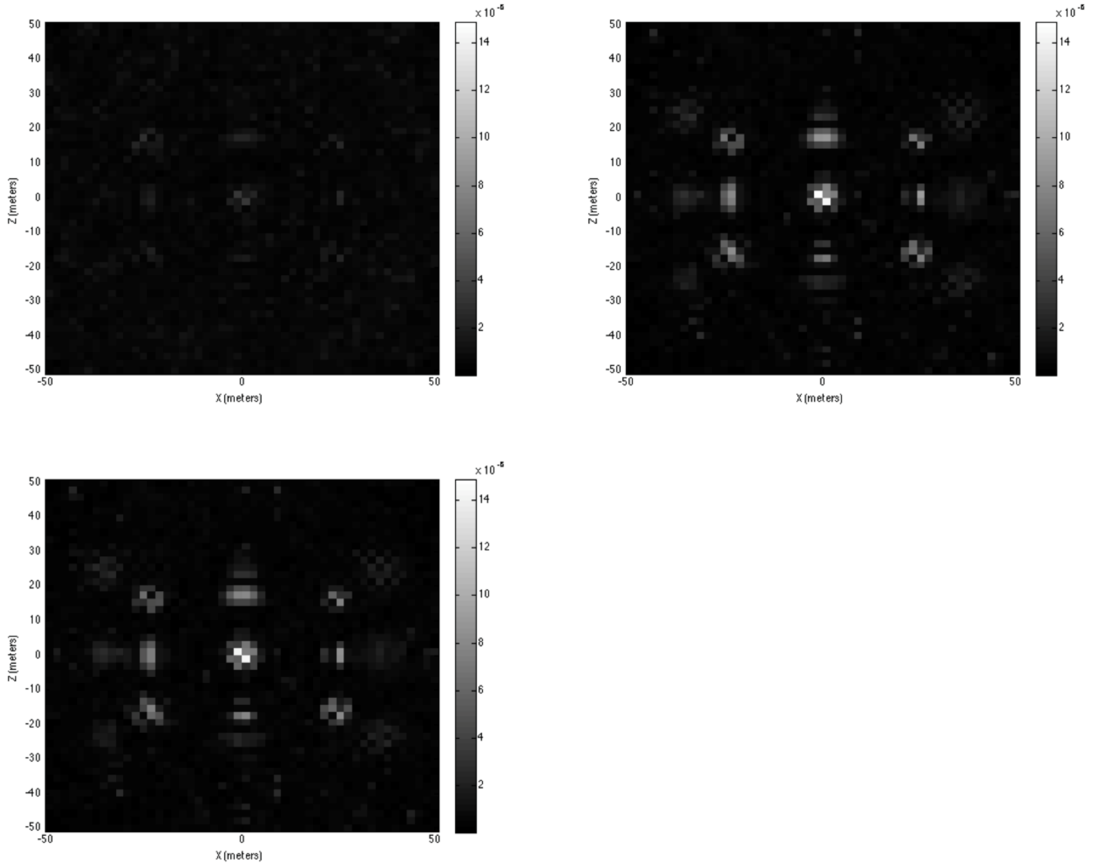

Figure 2. MIPs for nine point scatters subjected to high noise:
Top left: Unfocused scatter. Top right: Scatter focused by brute force. Bottom left: Scatter focused by gradient descent.

descent. By "stepping" in this direction, our iterative method approaches a minimum value for entropy

As discussed, this method makes no assumptions about the data on which it operates. However, this costs computational intensity. We initially developed a "brute force" algorithm that searched every possible answer for the minimizing choice. This required hours or days to optimize a typical image. We have since pursued faster techniques and optimized those using faster programming languages. Our final results are discussed below.

Experimental Results / Performance Gains

To verify our results we used a simulator to generate complex images from collections of point scatters. A point scatter is an ideal reflector of infinitesimally small size that works well for constructing ideal SAR images. For our performance tuning, we used a standard configuration used by students before us. Specifically, nine such point scatters were configured in a three dimensional grid. The responses from simulated radar pulses incident on the scene were generated and subjected to a relatively high degree of noise. Figure 2 shows the unfocused and focused result from our algorithm and the original brute force solution via maximum intensity plots (MIPs). Such plots are formed by taking two-dimensional slices of the three dimensional scene and adding them up, forming bright spots where reflective objects are located. As expected, the nine points can clearly be made out. Focusing the image, however, brings them into much sharper focus. Table 1 tabulates our performance results. Our optimization strategy fundamentally began with an algorithm change from a brute force technique to the aforementioned gradient descent algorithm. This yielded a modest improvement of about 400%. The major improvements, however, came from a port from

Table 1. Performance results measured using a generated image on a 64-core processor, except for iteration 4, which was conducted on NVIDIA's Quadro K620 GPU.

Entropy (ideal)	Entropy (high noise)	Lowest Achieved Entropy (focused)
5.39	9.28	6.52

Iteration	Technique	Execution Time (s)	Speed Up	Final Entropy
0	Brute force	125002.89	1	6.52
1	Gradient descent	25809.05	4.84	6.70
3	Gradient descent (threads)	620.07	201.59	6.70
4	Gradient descent (GPU)	323.69	386.18	6.70

the much slower prototyping language MATLAB to highly tuned and multithreaded C++. An additional boost was attained by using a graphics processing unit (GPU) instead of a traditional CPU. Our goal was to focus an image in less than a day. This goal was clearly attained and without loss in entropy minimization.

Conclusions

SAR imaging is a powerful and useful tool for a variety of applications. Limited by the requirement to use aircraft to sweep an aperture, however, images are difficult to collect if the collection requires secrecy or a near-ground aperture. By mounting a SAR system on a UAV, the Blue Team resolved some of the challenges, but introduced more. Due to inertial errors introducing severe phase offsets in the resulting pulse history, the resulting images from such a system are often extremely blurry. This note proposes an efficient implementation of a gradient descent algorithm to sharpen such SAR products. In comparison to the original, inefficient implementation, we have garnered a significant speed up at a limited cost to the entropy of the image. Overall, we achieved our goal of decreasing processing time from multiple days to under a day.

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