ECE Senior Capstone Project 2017 Tech Notes

Blue Team Project: Synthetic Aperture Radar for Unmanned Aerial Vehicles

Phase Gradient Autofocus (PGA) and Entropy Minimizing Approaches to SAR Autofocus

By Saurav Acharya, ECE '17

Inaccurate knowledge of the Synthetic Aperture Radar (SAR) antenna position during pulse transmission creates phase errors that add severe noise to radar images. This note compares the two main approaches to phase error correction, Minimum Entropy (MinEnt) and Phase Gradient Autofocus (PGA), and discusses additional techniques that can be used to improve autofocus performance.

Introduction

Synthetic Aperture Radar (SAR) is a high-resolution radar imaging technology used in side-looking aircraft that have a variety of applications in geomorphology, storm tracking, military surveillance, and terrain / ground feature mapping. Like traditional radars, airborne radars used in SAR imaging utilize a magnetron and an antenna to transmit the radio waves into the air. When the radio waves hit the target object, the antenna receives the reflected echo waves, and the time required for the echo to return can be used to calculate the distance between the antenna and the target. A side-looking airborne radar (SLAR) uses this concept to continuously take radar images of the swath of land below it.

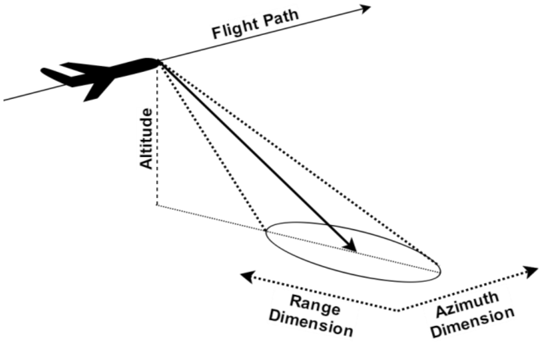


Figure 1: Geometry of a SLAR system.

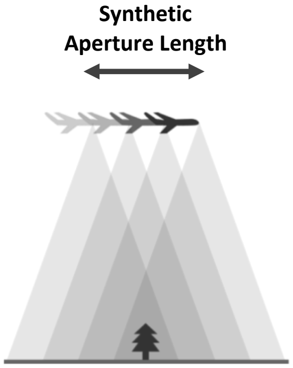


Figure 2: Pulse-by-pulse SAR imaging.

The quality of a typical SLAR image is limited by the azimuth resolution R_a along the dimension parallel to the aircraft's flight path. To achieve fine R_a, SLAR geometry requires the radar system to lower its altitude, increase its pulse frequency, or increase its physical antenna length. However, a low altitude can be impractical and high pulse frequency results in atmospheric absorption. Since increasing physical antenna length is also costly, the SAR technology is used to simulate a long antenna. The SAR antenna sends fixed-phase pulses as its platform moves across fixed distances, allowing it to build a large *synthetic* aperture that allows the SAR system to achieve fine R_a. A SAR system is lighter and less costly because it only requires one radiating element, making it especially effective for small-sized unmanned aerial vehicles (UAVs). Such UAV-mounted radars benefit over large aircrafts due to their lower costs, and their smaller size allows them to scan terrains which are otherwise difficult to access.

Phase Error Prevention & Correction

While SAR imaging significantly improves the radar image resolution, it relies on information from multiple 2D complex images. As a result, inconsistencies and errors present between images will degrade the combined high-resolution image. A major source of error comes from the unpredictable motion of the sensor platform. Inaccurate knowledge of the exact antenna position during pulse transmission will manifest in phase errors, which can degrade the "geometry linearity, resolution, image contrast, and signal-to-noise ratio" of the radar image (Koo et al., 2005). Therefore, most SAR systems take measures to minimize phase errors.

Prevention

Phase errors can be prevented by improving the accuracy of the radar’s positioning system within sub-wavelengths of the radar pulse (Wahl et al., 1994). This can be achieved through a differential GPS system that uses two GPS units, one on the radar platform and another on the stationary unit. When simply relying on GPS is insufficient, SAR systems use an additional inertial measurement unit (IMU) to predict position between GPS readings. However, due to budget limits, the UAV used in Blue Team's capstone project is limited to only the differential GPS. Therefore, it will be crucial to rely on robust autofocus techniques in order to correct phase errors.

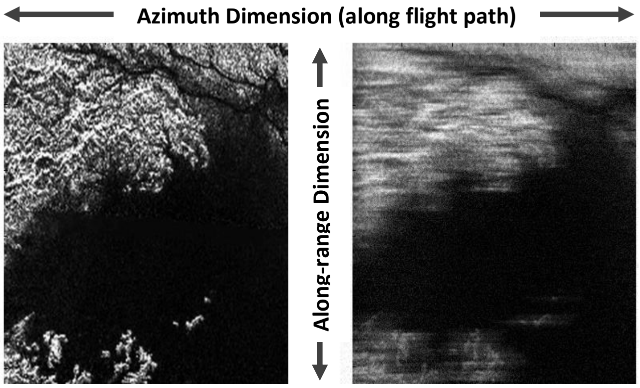


Figure 3: Example of simulated phase error defocusing on a typical SAR image. Photo courtesy NASA/JPL-Caltech.

Phase Error Correction via Autofocus

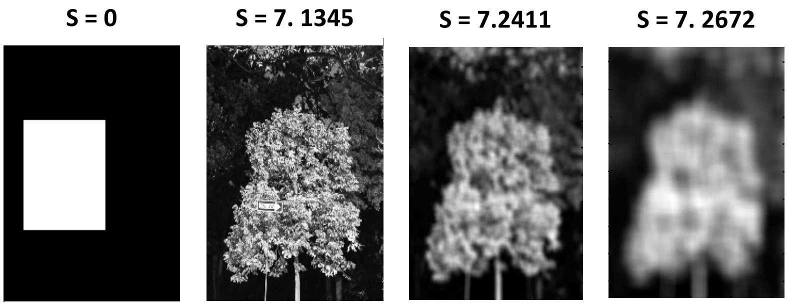
The SAR system continuously takes 2D complex radar images as it moves through its flight path. The positioning errors present during each pulse manifests as phase errors, which add noise in the cross-range (azimuth) dimension of the radar image. The phase error function, denoted by $\phi(k)$, indicates what phase offset is required for each of k pulses in order to correct the image. If $\phi(k)$ is known, it can be used to correct the measured pulse history $y(m,k)$ to obtain the phase-corrected pulse history $z(m,k)$ as follows:

$$z(m,k;\ \phi) = y(m,k) * e^{j\phi(k)}$$

There are two main approaches to estimating the phase error: non-parametric and model-based. Model-based autofocus techniques such as Minimum Entropy (MinEnt) Autofocus often use a cost function to estimate $\phi(k)$ and reconstruct the radar image. Non-parametric autofocus techniques such as Phase Gradient Autofocus (PGA) instead directly analyze and manipulate the blurry 2D radar images before estimating $\phi(k)$.

Phase Gradient Autofocus

The PGA algorithm is an industry-grade autofocus technique that has been well researched and extended many times to improve its performance. The main steps of PGA involve (1) segmenting the noisy radar image into bins along the range dimension, (2) selecting bins with the highest signal to noise ratio (SNR) and centering the strongest response in each bin through circular shifting, and (3) windowing the bins to remove other weaker responses (Wahl et al., 1994; Azouz et al. 2015). After these steps, various techniques such as maximum likelihood estimate (MLE) can be used to estimate the phase error function $\phi(k)$ and undo the phase error repeatedly, until the algorithm converges.


S = 0

S = 7. 1345

S = 7.2411

S = 7. 2672

Figure 4: Examples of image entropy.

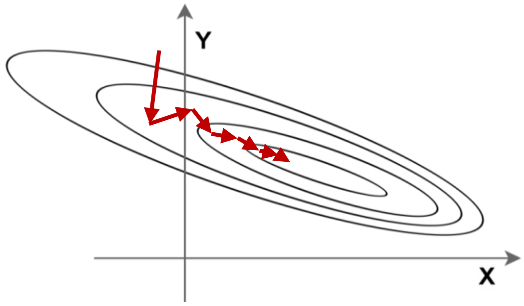


Figure 5: Gradient descent on a 2-variable function.

Minimum Entropy Autofocus

Entropy Minimization

Entropy is a statistical measure of randomness that correlates inversely with the image sharpness. A focused image will yield lower entropy than its blurry counterparts. Therefore, Minimum Entropy Autofocus (MinEnt) algorithms use the image entropy as the cost function to maximize image sharpness. In order to autofocus the noisy image $y(m, k)$, we must compute the phase error function estimate $\hat{\phi}(k)$ that minimizes the entropy of the phase-corrected image. Since $\hat{\phi}(k)$ is a vector consisting of K phase offsets, estimating $\hat{\phi}(k)$ may be a computationally expensive task if the number of pulses K is large.

Gradient Descent and Optimizations

Rather than using brute force and trying out all possible phase offsets, we utilize the gradient descent algorithm. In the case of MinEnt, gradient descent is used to find the vector $\hat{\phi}(k)$ that minimizes the entropy function for the radar image $S\big(\phi(k)\big)$. The gradient descent algorithm does this by iteratively stepping along the *gradient* of the entropy function $\nabla S(\phi(k))$, which points to the direction at which the entropy decreases the fastest. Essentially, in each step along the gradient, the vector $\hat{\phi}(k)$ is modified slightly until the algorithm converges and the image entropy settles at a local minimum. The size of this step is determined by the learning rate constant α. A low α will increase the time it takes for the algorithm to converge, while a large α may modify $\hat{\phi}(k)$ too fast and ‘overshoot’ the local minimum. Therefore, the performance of gradient descent can be improved by finding an ideal initial learning rate α or adding momentum to α via methods such as Adaptive Moment Estimation (Ruder, 2016).

The gradient descent algorithm optimizes $S\big(\phi(k)\big)$, which is a function of $k = 1 .. K$ dimensions. Therefore gradient descent can still be expensive if the number of pulses K is large. Luckily by making assumptions about the SAR platform we can reduce S’s dimensionality. Considering how the SAR platform has inertia in the real world, its movement can be roughly modeled by a continuous and smooth function. This means that the phase errors present in adjacent pulses are actually codependent. Azouz et. al. noticed this relationship and were able to speed up the gradient descent algorithm by running it on fixed orders of Discrete Cosine Transform (DCT) coefficients. In other words, rather than using K phase error offsets, they were able to accurately model the phase error function $\phi(k)$ using only 20-30 coefficients of DCT. This significantly decreases the time required for the gradient descent optimization to converge and find the smoothed phase error estimate.

PGA vs. MinEnt

While PGA is an industry-grade algorithm that effectively removes high-order phase errors, it may not be suitable for the SAR system used in our capstone project. As the previous year's Blue Team

2016 observed, PGA demands radar systems with a large physical aperture in the segmentation step of PGA (Wahl et al., 1994; Pfosi, 2016). Moreover, the extreme motion errors caused by the lack of an IMU in our SAR system can create phase errors that are too severe to be recovered through PGA. Since PGA is a more involved autofocus technique with more steps, consequently it also has more parameters such as the cutoff regions in the windowing step. These steps need to be manually fine-tuned by an expert, which is not desired in an autofocus algorithm.

Methods involving entropy minimization have proven to be even more effective than PGA in a qualitative research conducted by Morrison et. al. Although the MinEnt method ran about ten times slower than PGA, MinEnt outperformed PGA in a target detection test by detecting 57 targets compared to PGA's 25 out of 63 total targets. MinEnt's slow speed can be alleviated through the performance improvements we discussed, such as DCT smoothing and smarter adaptation of the gradient descent learning rate. With recent advances in computing power, the computational demands of entropy minimizing approaches to SAR autofocus are alleviated and MinEnt may be preferred over the traditional PGA due to their superior performance.

Conclusion

In comparison to traditional radar, SAR produces images with finer azimuth resolution by building a synthetic aperture over the SAR platform's flight path. Therefore, due to their small size, lower costs and superior resolution, SAR systems are becoming an effective replacement for traditional airborne radars.

SAR imaging relies on information from multiple radar images, so positioning errors present in the images accumulate to form phase errors in the resulting combined image. The industry-standard Phase Gradient Autofocus (PGA) technique works well for SAR systems with larger physical aperture, but the Minimum Entropy Autofocus approach is more appropriate for the small-aperture SAR system used by the Blue Team's capstone project. Although they are slower, entropy minimizing algorithms have proven to be just as effective as PGA, and their performance can be improved further by integrating DCT smoothing and more adaptive gradient descent algorithms. If a faster autofocus algorithm is needed in the future, the Blue Team should utilize the PGA algorithm only after integrating a more reliable positioning system that includes an inertial measurement unit (IMU).

References

1. Azouz, A. A., & Li, Z. (2015). Improved phase gradient autofocus algorithm based on segments of variable lengths and minimum-entropy phase correction. *IET Radar, Sonar & Navigation, 9*(4), 467-479.
2. Koo, V., Lim, T. S., & Chuah, H. T. (2005). A Comparison of Autofocus Algorithms for SAR Imagery. *PIERS Online, 1*(1), 16-19.
3. Kragh, T. J. (2006). Monotonic Iterative Algorithm For Minimum-Entropy Autofocus. *Proceedings, Adaptive Sensor Array Processing (ASAP) Workshop*.
4. Morrison, R., & Munson, D. (n.d.). An experimental study of a new entropy-based SAR autofocus technique. *Proceedings. International Conference on Image Processing*.
5. Pfosi, J. (2016). Synthetic Aperture (SAR) Autofocus Techniques. *Tufts ECE Senior Design Handbook - 2016 Tech Notes*.
6. Ruder, S. (2016, December 17). An overview of gradient descent optimization algorithms. Retrieved from http://sebastianruder.com/optimizing-gradient-descent/index.html
7. Wahl, D., Eichel, P., Ghiglia, D., & Jakowatz, C. (1994). Phase gradient autofocus-a robust tool for high resolution SAR phase correction. *IEEE Transactions on Aerospace and Electronic Systems, 30*(3), 827-835.
8. Yegulap, A. F. (1999). Minimum Entropy SAR Autofocus. *Proceedings, Adaptive Sensor Array Processing (ASAP) Workshop.*