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ABSTRACT

Along-Track Interferometry (ATI) has been widely used for ground moving target indication (GMTI) in airborne synthetic aperture radar (SAR) systems. In ideal cases, the ATI phase obtained using two phase centers that are aligned in the along-track dimension yield clutter-only pixels with zero phase. However, the platform’s motion may create a cross-track displacement between the two phase centers and in turn offset the phase centers’ baseline from the along track dimension. This cross-track offset leads to non-zero phase for clutter-only pixels, necessitating calibration for accurate GMTI. This paper proposes a blind calibration method to correct the along-track baseline error in ATI-SAR systems. The success of the proposed method is shown on a set of measured data from the Gotcha sensor.

1. INTRODUCTION

Synthetic aperture radar (SAR) imaging was invented in the 1950s and has since been under continuous development. It is capable of imaging large swaths of terrain and all manners of objects visible to instruments operating in the RF spectrum. Along-track interferometry (ATI) is a well-known technique based on SAR images obtained from two phase centers separated by some distance in the along-track dimension.¹ ATI provides the capability to cancel out the clutter scene (stationary background) and emphasize moving targets signatures by correlating the images from the two phase centers.

Ideally the displacement between the two phase centers should be purely in the along-track dimension. However, if there is a cross-track offset as well – i.e. the crab angle is non-zero – the background phase must be calibrated before performing target detection. Different methods have been proposed in the literature to calibrate the ATI phase. Known reflector arrays (calibration targets) can be used to calibrate the ATI phase.² Calibration targets may not always be available, therefore blind phase calibration techniques are necessary for unfamiliar environments. The background phase can be removed in an iterative manner by estimating the “phase shift” as a function of cross-range.³

In this paper we discuss a new fast, non-iterative method for blind background interferometric phase calibration that does not require calibration targets or iteration. The background phase exhibits an oscillatory behavior in the range, cross-range (angle) domain. In this paper the terms angle and cross-range are used interchangeably, as both quantities vary by a linear scaling factor. This behavior appears nonlinear (near-constant phase values for isorange arcs) in the Cartesian coordinate system used for imaging.

A coordinate system transformation is applied to the input interferometric phase converting it from Cartesian to range-angle. This simplifies estimation of the background phase, since each cross-range bin become a row of the transformed phase in the range-angle domain. After the forward coordinate system transform, a low-pass estimate of the background phase is obtained and an inverse coordinate system transformation is applied. In the \((x,y)\) domain, the estimated background phase is subtracted from the input phase, yielding the calibrated phase.

*The work described here was supported by the Defense Advanced Research Project Agency (DARPA), Arlington, VA, under SBIR Phase II contract No. D11PC20007. The views expressed are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. Distribution Statement “A” (Approved for Public Release, Distribution Unlimited). Send correspondence to: faruk@cptnj.com or murthy@cptnj.com.
2. BACKGROUND

2.1 Along-Track Interferometry

The interferogram $I_{AB}(x,y)$ can be constructed by computing the zero-lag cross correlation between the complex-valued SAR images $I_A(x,y) = |I_A(x,y)|e^{j\phi_A(x,y)}$ from the first phase center and $I_B(x,y) = |I_B(x,y)|e^{j\phi_B(x,y)}$ from the second phase center. The two phase centers ‘A’ and ‘B’ are separated in the along-track dimension by some distance $D$. The basic interferogram is given by

$$I_{AB}(x,y) = I_A(x,y)I_B^*(x,y) = |I_A(x,y)||I_B(x,y)|e^{j\phi(x,y)}$$

(1)

where $\phi(x,y) = \phi_A(x,y) - \phi_B(x,y)$. During SAR imaging, if the platform parameters are known accurately, stationary targets can be accurately phase compensated in both $I_A(x,y)$ and $I_B(x,y)$. The phases of pixels containing only stationary scatterers combine destructively so that $\phi = 0$ for those pixels since

$$\phi = \frac{4\pi D}{\lambda V_p} v_r,$$

(2)

where $v_r$ is the line of sight target velocity, $\lambda$ is the wavelength corresponding to the transmit center frequency and $V_p$ is the platform velocity. Therefore for a scene containing only stationary targets (clutter) the interferogram phase should be zero and those pixels containing the observed target signature will have nonzero values. However, when where is some cross-track offset between the two phase centers used for interferometry (i.e. nonzero crab angle) the background phase does not cancel as expected. The objective of the method presented in this paper is to enhance the observed target signature by suppressing nonzero background phase values via phase calibration.

2.2 Gotcha Phase History Data

The Air Force Research Laboratory (AFRL) Gotcha Program has released a set of SAR data to provide researchers with a source of real radar data for various applications. The results presented here are based on a related data set provided by AFRL. In the Gotcha data, the collection scene center is defined to be $(0,0)$ in the plane coordinate system. SAR images are formed using the backprojection algorithm as described in. Fig. 1 shows the SAR image of the area of interest at a $0.25 \times 0.25$ meter resolution. The corresponding truth data for the processing time interval indicate there is at least one control target present in the area imaged.

Fig. 2 shows the raw (uncalibrated) ATI phase $\phi_{AB}(x,y)$ corresponding to the first and second HH polarized channels in the phase history data. As shown in Fig. 2, the background phase corresponding to stationary ground clutter is not equal to zero. It differs from the ideal case due to the sensor geometry and must be calibrated to apply threshold-based target detection. Upon casual inspection, it is not easy to discern moving targets, or even potential target candidates in the raw phase. Other methods that do not rely on a zero-phase background may also be less successful given the oscillatory behavior observed in the unprocessed phase.

Figure 1: SAR image of area of interest
3. PHASE CALIBRATION

Fig. 3 shows a high-level flow diagram of the phase calibration processing. After the basic interferogram is computed, a 2D averaging filter is applied to the raw phase. In this pre-processing step, the averaging filter can be replaced with a median filter. Fig. 4 shows the result of the pre-processing step using a $9 \times 9$ boxcar filter $h_1(x, y)$ to the raw phase.

$$\tilde{\phi}_{AB}(x, y) = \phi_{AB}(x, y) \odot h_1(x, y)$$

(3)

The size of the 2D pre-processing filter is image resolution dependent and should be chosen accordingly to preserve the target signature.

After pre-processing a coordinate system transformation is applied to the filtered phase, converting it from Cartesian to polar. Let $(x, y)$ be the standard Cartesian coordinates, and $r$ and $\theta$ the standard polar coordinates then,

$$r = \sqrt{x^2 + y^2}$$

(4)

$$\theta = 2\tan^{-1}\left(\frac{y}{r+x}\right).$$

(5)

In (5), the four-quadrant inverse tangent formula is used in place of $\tan^{-1}(\cdot)$ to distinguish the quadrants of the polar angles.

Spatial interpolation is necessary to achieve a continuous polar grid $(r, \theta)$. Natural neighbor interpolation is an effective method for interpolation and is used when performing the coordinate system transformations. The interpolated pixel value using this method is given by

$$G(r, \theta) = \sum_{i=1}^{n} w_i \tilde{\phi}_{AB}(x_i, y_i),$$

(6)

where $n$ is the number of natural neighbors, $G(r, \theta)$ is the interpolated pixel value on the polar grid $(r, \theta)$, $w_i$ are the weights from $\tilde{\phi}_{AB}(x_i, y_i)$ are the known data on the Cartesian grid $(x_i, y_i)$.

Fig. 5 shows the ATI phase in the range and cross-range domain after applying the coordinate system transform. As seen from Fig. 5, the curvature of the uncalibrated phase (observed in Fig. 4) is flattened after the coordinate system transformation. Thus, the range and cross-range dimensions are aligned with the pixels rows and columns.

Once the uncalibrated phase has been rendered into the range/cross-range domain, the background phase can be estimated row by row (i.e. for each cross-range bin). Since the background phase oscillates slowly, a lowpass filter can be used to estimate the background phase

$$\hat{G}(r, \theta) = G(r, \theta) \odot h_2(r)$$

(7)
where $h_2(r)$ is 1-D smoothing filter in the range dimension.

Fig. 6 shows the original (red line) and smoothed ATI phase (blue line) for a single cross-range cell. As seen from Fig. 6, potential moving targets create peaks and their signatures do not follow the background phase trend. The phase for each cross-range cell is slowly varying so that the filter used for estimation is chosen to be a lowpass smoothing filter. A 31-sample averaging filter was used in this example, as it provides a good estimate for the background phase and mainly preserves the observed spikes. Note that the filter length will vary depending on the grid resolution, and should be adjusted accordingly to preserve potential target signatures.

Fig. 7 shows the estimated phase calibration map by repeating the process illustrated in Fig. 6 for all cross-range cells independently. The background phase can be calibrated in $(r, \theta)$ by subtracting the estimated background phase

$$
\phi_{cal}(r, \theta) = G(r, \theta) - \tilde{G}(r, \theta).
$$

However, converting the calibration map to Cartesian coordinates reduces the numerical error propagated through the coordinate system transforms. In practice, this error is typically on the order of $10^{-6}$ for the examples shown.
here. This may vary depending on several factors including the size of the area imaged, and the number of pixels used. As a complement of equation 4 and 5, the transform from polar coordinates to Cartesian coordinates is defined as

\[ x = r \cos \theta, \quad y = r \sin \theta. \quad (9) \]

The phase calibration matrix \( \phi_{\text{cal}}(x, y) \) in Cartesian coordinates can be achieved after the natural neighbor interpolation,

\[ \phi_{\text{cal}}(x, y) = \sum_{k=1}^{n} w_k \tilde{G}(r_k, \theta_k). \quad (10) \]

Fig. 8 shows the phase calibration matrix \( \phi_{\text{cal}}(x, y) \) in the Cartesian coordinate system. Note that due to the nature of the coordinate system transformation the phase calibration matrix has no values near the upper and lower boundary regions.

Finally, the calibrated ATI phase \( \hat{\phi}_{AB} \) is achieved by subtracting the phase calibration map from the smoothed ATI phase as,

\[ \hat{\phi}_{AB}(x, y) = \tilde{\phi}_{AB}(x, y) - \phi_{\text{cal}}(x, y). \quad (11) \]

As a final step, a 2D median filter can be applied to the calibrated phase to reduce the speckle noise and facilitate target detection. The Fig. 9 shows the calibrated ATI phase after post-processing (median filtering); here a potential target signature is indicated. Note that potential target signatures are clearly visible to inspection in the calibrated phase shown in Fig. 9 compared to the raw ATI phase in Fig. 2.
4. TARGET GEOLOCATION ESTIMATION ON GOTCHA

The proposed blind phase calibration method is integrated into the target geolocation technique from in\(^8\) to improve the target geolocationing accuracy. A controlled moving target’s signature (Vehicle ‘G’) is observed within the area of interest shown in Fig. 1 for 20 seconds. The total observation interval was split into 10 non-overlapping 2 second integrations for target detection and geolocation. Fig. 10 shows the results of applying the geolocation procedure from\(^8\) to the 10 consecutive frames of data using the proposed phase calibration method. By comparison with the available truth data, the average geolocation error was computed to be 16.17m.

5. CONCLUSIONS

A new fast, blind calibration method is proposed to estimate the along-track phase error due to the cross-track displacement of the phase centers used for interferometry. Unlike the other methods in literature, the proposed method does not need either a priori information or iterative processing. The success of the proposed method is shown on a measured Gotcha data set. The proposed method was integrated with the target geolocation procedure and applied to the Gotcha data. The controlled target was geolocated with an average accuracy of 16.17m.

Target detection can also be performed using sparsity based techniques in the range-angle domain since targets are sparse for each cross-range bin. Once target detection has been performed, computer vision and artificial intelligence techniques can be applied for automatic multi-target geolocation using.\(^8\)
Acknowledgment

The authors wish to acknowledge Mr. Vincent Sabio, Program Manager, Strategic Technology Office (STO) at DARPA for his support as well as his encouragement to test and validate these approaches on measured data.

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