Bistatic SAR Image Registration Accuracy

Ellen E. Laubie\textsuperscript{1,2}, Dr. Brian D. Rigling\textsuperscript{3}, and Dr. Robert P. Penno\textsuperscript{1}
\textsuperscript{1}Department of Electrical and Computer Engineering, University of Dayton, Dayton, OH
\textsuperscript{2}Sensors Directorate, Air Force Research Labs, Wright Patterson Air Force Base, OH
\textsuperscript{3}Department of Electrical Engineering, Wright State University, Dayton, OH
Email: ellen.laubie@us.af.mil, brian.rigling@wright.edu, rpenno1@udayton.edu

Abstract — An investigation of the effect of bistatic angle on the accuracy of registering a monostatic image of a target to a bistatic image of the same target is presented in this paper. Cross-correlation registration degradation is related to the decorrelation of a monostatic image with a bistatic image with respect to bistatic angle. This paper illuminates the absence of an image registration technique that is specifically designed for aspect-diverse bistatic images. Traditional monostatic image registration is not sufficient for bistatic images.

Index Terms — bistatic radar, correlation, image registration, synthetic aperture radar

I. INTRODUCTION

The investigation of bistatic synthetic aperture radar (SAR) image registration accuracy in this paper is motivated by the currently renewed interest in bistatic radar. As Willis and Griffiths note in [1], interest in bistatic radar is cyclical: receiving attention in highs and lows over time. Currently, the radar community is experiencing a surge in bistatic radar interest due to its ability to separate transmitting and receiving platforms. This separation of platforms allows the receiving platform to remain passive and allows bistatic systems to utilize transmitters of opportunity [1]. In addition, multiple transmitters and/or receivers may be used simultaneously to provide additional information about a target of interest. It is the latter capability that is the focus of this paper.

Multiple cross-platform images can be used for change detection, to improve automatic target recognition (ATR), and to form 3-D images, as well as other applications. However, while multiple bistatic views provide many benefits, the unique nature of bistatic scattering responses may hinder the registration of bistatic images with monostatic images in instances where acceptable motion compensation is not achieved by the platforms’ GPS/INS. The experiments in this paper investigate the effect of bistatic angle on the cross-correlation registration of a monostatic image of a target to a bistatic image of the same target (when the transmitter is kept in the same location).

To date, there has been no published research on registration techniques specifically designed for bistatic SAR. However, research on general image registration and change detection has been extensive. In [2], Zitová and Flusser presented a 2003 survey of image registration methods (irrespective of imaging platform) that covered 224 publications on the subject. Several other publications have covered the topic of image registration specifically for images generated using a monostatic SAR platform [3] [4] [5]. This paper investigates the use of a cross-correlation registration technique for bistatic systems to demonstrate that these traditional monostatic SAR registration methods are not sufficient for bistatic SAR systems.

The remainder of this paper is organized as follows. Section II describes the simulated bistatic SAR data used in this paper. Section III outlines the normalized circular cross-correlation technique used in this paper. Section IV examines the effect of bistatic angle on the correlation between a monostatic image of a target and the bistatic image of the same target. Section V investigates how correlation and bistatic angle affect registration accuracy when a monostatic image of a target is registered to a bistatic image of the same target. Finally, Section VI concludes with a discussion of the results and a projection for future research.

II. SIMULATED BISTATIC SAR DATA

An electromagnetic (EM) scattering simulator, Raider Tracer, was used to generate the bistatic SAR data used in this paper due to its open-source and non-military nature. The version used in this paper was a bistatic extension of the monostatic EM scattering simulator outlined in [6] [7]. Raider Tracer was written for MATLAB and is a physical optics (PO)-based RF prediction script that simulates the far-field scattering response of a given target facet model to a bistatic (and monostatic for a bistatic angle of zero) radar. The simulator assumes that the target is in the far-field and that all facets are perfect electrical conductors (PEC). The effects of diffraction and polarization are excluded. Users provide the target facet model, the number of bounces collected for each simulated ray, and lists of the frequencies and azimuth-elevation angle pairs to be used in the simulation. The simulated response is a two-dimensional complex-valued array indexed by frequency and azimuth-elevation angle pair [6].
Fig. 1. Overhead views (top row) and rotated side views (bottom row) of the faceted civilian vehicle target models used to generate simulated bistatic SAR scattering responses: Nissan Maxima (left), Toyota Camry (center), and Toyota Tacoma (right).

Three faceted civilian vehicle targets were used for the experiments in this paper: a Nissan Maxima, a Toyota Camry, and a Toyota Tacoma. Views of the faceted targets can be seen in Fig. 1. All three targets have the same orientation relative to the bistatic SAR geometry with the x-y plane as the ground plane, and the center of the car at \((0,0)\). All three vehicles point in the positive-x direction.

Fig. 2. Overhead views of the bistatic geometry for two experiments. Views show azimuth only (elevation is constant throughout time and experiments). The bistatic angle, \(\beta\), is altered each experiment so that the transmitter remains in the same location (centered at \(0^\circ\)) and the receiver is \(\beta^\circ\) away from the transmitter.

Bistatic geometry and experimental parameters are the same for the simulated scenarios in this paper as they are for the bistatic SAR ATR investigation in [8]. The movement of the receiver and transmitter over the SAR aperture can be viewed in Fig. 2 and is as follows. The elevations of both the transmitter and receiver remain constant such that \(\theta_t(\tau) = \theta_r(\tau) = 30^\circ \forall \tau\) for each experiment. The azimuth angles traversed by each platform for each experiment is \(\Delta \phi_t = \Delta \phi_r = 3^\circ\) so that the bistatic angle, \(\beta\), remains constant with respect to slow time over the course of one scenario. The transmitter aperture center is kept constant at \(0^\circ\) for all scenarios and the bistatic angle is altered in each scenario so that the receiver azimuth is \(\phi_r(\tau) = \phi_t(\tau) + \beta\). The distance to the target is assumed to be large enough to be considered far-field.

Bandwidth is kept constant at \(B = 500MHz\). Range resolution is dependent on the bistatic angle and bandwidth and is calculated as

\[
\delta_r = \frac{c}{2B\cos(\beta/2)},
\]

where \(c\) is the speed of light [1]. For a constant bandwidth and increasing bistatic angle between \(0^\circ\) and \(90^\circ\), the range resolution increases exponentially with respect to \(\beta\). For the experiments in this paper, the smallest range resolution is \(\delta_r = 0.3m\) when \(\beta = 0^\circ\) and the largest is \(\delta_r = 0.44m\) when \(\beta = 90^\circ\).

The simulated frequency range is \(f \in [f_c - B/2, f_c + B/2]\) with a center frequency of \(f_c = 10GHz\). Both the frequency range and transmitter-receiver locations are sampled \(N = 256\) times over the duration of each simulation.

Sidelobes are suppressed using Taylor weighting with a peak sidelobe level relative to the mainlobe peak of -35dB and five series terms. Images are formed using the bistatic backprojection algorithm (BPA) and oversampling factor of 8 [1]. Each image is \(54 \times 54\) pixels with \(0.15m \times 0.15m\) pixels (half of the initial range resolution). Example images of the three targets at three different bistatic angles can be seen in Fig. 3.
III. CROSS-CORRELATION

Normalized circular cross-correlation is used for two purposes in this paper. First, cross-correlation is employed to investigate the correlation between a monostatic image of a target and a bistatic image of the same target with respect to bistatic angle. This demonstrates the degradation in correlation with respect to bistatic angle. Second, a cross-correlation technique is used to register a monostatic image of a target to a bistatic image of the same target. Normalized cross-correlation, in general, is utilized because of the simplicity of its implementation, and due to its popularity as a monostatic registration technique. Circular cross-correlation, specifically, is used due to its efficient Fast Fourier Transform (FFT) implementation. For the purposes of this paper, it is assumed that there is sufficient white space around the targets such that circular cross-correlation is equivalent to cross-correlation. Images are initially normalized to have zero mean and unit variance. Circular cross-correlation is implemented using the two-dimensional FFT so that the autocorrelation at zero lag is identically 1.0. The normalized cross-correlation coefficient is simply the normalized cross-correlation for zero lag, $C_{AB}(0,0)$, and indicates the correlation between the two images when they overlap completely.

IV. DEGRADATION OF CORRELATION

The degradation of correlation between a monostatic image and bistatic images with respect to bistatic angle indicates the difficulties with using similarity measures to register images from different aspects (particularly aspects that originate from bistatic platforms). A bistatic SAR canonical scattering model of a flat square plate from [9] is used to demonstrate this degradation in correlation.

In [9], Jackson et al. developed three-dimensional parametric models to describe canonical SAR scattering responses of several geometric objects. In particular, a simple rectangular flat plate of length, $L$, and height $H$, located in 3D space at $(0,0,0)$ can be modeled simply in terms of plate length, plate height, and receiver and transmitter elevations and azimuths. That model, as defined in [9] is

$$M_{plate}(k, \phi_t, \theta_t, \phi_r, \theta_r) = \frac{jk}{\sqrt{\pi}} \cdot L \cdot H \cdot sinc\left(\frac{kL}{2} \sin\phi_t \cos\theta_t \sin\phi_r \cos\theta_r\right) \cdot sinc\left(\frac{kH}{2} \sin\theta_t \sin\theta_r\right),$$

where $k = 2\pi f / c$ is the wavenumber. Scattering responses of a $1m \times 1m$ flat plate are generated using this model and the same bistatic geometry and SAR frequencies outlined in Section II. Images are generated from the modeled scattering responses using the same BPA parameters also outlined in Section II. A model and corresponding image are produced for each bistatic angle between $\beta = 0^\circ$ and $\beta = 90^\circ$ at $1^\circ$ intervals. Cross-correlation is then calculated between the image of the plate as viewed by a monostatic platform ($\beta = 0^\circ$), and the image of the same plate as viewed by a bistatic platform (with bistatic angle $\beta$). As previously shown in Fig. 2, the transmitter aperture remains centered at $0^\circ$, and the receiver aperture is centered at $\beta^\circ$.

Cross-correlation of the magnitude images of the flat plate with respect to bistatic angle can be seen in Fig. 4. This figure reveals how cross-correlation between the images degrades as the bistatic angle increases. Cross-correlation is relatively high when the transmitting and receiving apertures are overlapping (between $\beta = 0^\circ$ and $\beta = 3^\circ$). This correlation degradation is indicative of the accuracy of similarity measure registration for aspect diverse image registration.

V. REGISTRATION

The effect of bistatic angle on image registration is examined for scenarios where the sensed image is a monostatic image of a target, and the reference image is a bistatic image of the same target. Image registration is performed using normalized circular cross-correlation by selecting the 2-D lag that maximizes the circular cross-correlation image from Section II [2]. As previously mentioned, the transmitter is co-located for each pair of images at $(\phi_t, \theta_t) = (0^\circ, 30^\circ)$ and the receiver is shifted by $\beta^\circ$ in azimuth from the reference image to the test image.
Fig. 5. Noisy images for two of the targets at $\beta = 0^\circ$ (monostatic): Nissan Maxima (left) and Toyota Camry (right). Noise was added to the complex phase history data to achieve a signal-to-noise ratio of $SNR = -40dB$ (8.16dB in the image domain). The back-projection algorithm has a low-pass filter effect on the AWGN noise in the image domain. Images are shown in a dB scale.

Original, non-noisy data is generated using Raider Tracer and the aforementioned civilian vehicle targets (Toyota Camry, Nissan Maxima, and Toyota Tacoma). Three hundred noisy test images are also generated for each target for each bistatic angle (including the monostatic case) between $\beta = 0^\circ$ and $\beta = 90^\circ$ at $1^\circ$ intervals (for a total of 81,900 noisy test images). Additive White Gaussian Noise (AWGN) is added in the phase history domain by estimating the variance of the original signal, calculating the noise variance needed to achieve a desired signal-to-noise ratio (SNR), and then adding complex AGWN with the necessary noise variance. For the experiments in this paper, an SNR of $-40dB$ in the phase history domain is implemented.

Examples of two noisy images can be seen in Fig. 5. The back-projection algorithm has a low-pass filter effect on the phase-history domain noise, so that the image domain SNR is 8.16dB.

For the purposes of this paper, registration offset is assumed to be linear (although the test images are not actually shifted). Normalized circular cross-correlation registration produces a registration location at the point where the cross-correlation image is maximized. The registration location has two indices: one in the x-direction and one in the y-direction. Since the test images are not actually shifted, a correct registration offset for any image pair would be an x-y offset of $(x, y) = (0, 0)$.

Registration accuracy is measured as the root mean squared error (RMSE) over the 300 test images for each bistatic angle. The error for a single registration, $\epsilon$, is determined by the Euclidean distance (in meters) from the actual registration location $(0,0)$ to the estimated registration location $(x_r, y_r)$ [10], where the estimated registration location is the lag that maximizes the cross-correlation image. The RMSE is calculated for each civilian vehicle target for each bistatic angle and plotted versus the bistatic angle of the reference image.

A plot of the RMSE versus bistatic angle for each target when the images are complex can be seen in Fig. 6. Even with added noise, registration is highly accurate for very small bistatic angles. However, as with cross-correlation in Section III, a monostatic image of a target does not register well to a bistatic image of the same target for bistatic angles of $\beta > 4^\circ$. This degradation in registration accuracy occurs when the transmitting and receiving apertures no longer overlap.

Fig. 6. Registration accuracy when a monostatic complex image of a target is registered to a bistatic complex image of the same target. Accuracy is plotted as the root mean squared error (RMSE) in meters versus the bistatic angle for the Toyota Camry, Nissan Maxima and Toyota Tacoma.

A plot of the RMSE versus bistatic angle for each target when the images are complex can be seen in Fig. 6. Even with added noise, registration is highly accurate for very small bistatic angles. However, as with cross-correlation in Section III, a monostatic image of a target does not register well to a bistatic image of the same target for bistatic angles of $\beta > 4^\circ$. This degradation in registration accuracy occurs when the transmitting and receiving apertures no longer overlap.

A plot of the RMSE versus bistatic angle for each target can be seen in Fig. 7. The images used for registration are the magnitudes of the original complex images. The RMSE for the magnitude images is slightly lower overall than the RMSE for the complex images. However, the same trend appears. Registration accuracy is very high for very small bistatic angles, but decreases substantially for larger bistatic angles. These findings indicate that traditional registration techniques, such as normalized circular cross-correlation are not suited to register images that originate from systems separated by bistatic angles that large relative to the aperture size.
VI. CONCLUSION

This paper presents analysis of a traditional cross-correlation-based image registration technique for bistatic image registration. A model-based study of the correlation between a monostatic image of a flat plate and a bistatic image of a flat plate demonstrates a significant decrease in correlation as bistatic angle increases. Degradation is particularly steep for bistatic angles where the transmitting and receiving apertures do not overlap. Further analysis is performed using simulated bistatic SAR data and cross-correlation image registration. This analysis revealed that traditional monostatic image registration techniques are not sufficient for bistatic images.

Future work will entail developing an image registration method that exploits the unique scattering behavior of targets illuminated by a bistatic platform. Tangential work in [8] investigates the use of aspect-diverse bistatic SAR images for improving ATR. Future work will also investigate the effect of non-perfect registration on this aspect-diverse ATR technique.

REFERENCES


