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Refocus of constant velocity moving targets in synthetic aperture radar imagery

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ABSTRACT

The detection and refocus of moving targets in SAR imagery is of interest in a number of applications. In this paper we address the problem of refocusing a blurred signature that has by some means been identified as a moving target. We assume that the target vehicle velocity is constant, i.e., the motion is in a straight line with constant speed. The refocus is accomplished by application of a two-dimensional phase function to the phase history data obtained via Fourier transformation of an image chip that contains the blurred moving target data. By considering separately the phase effects of the range and cross-range components of the target velocity vector, we show how the appropriate phase correction term can be derived as a two-parameter function. We then show a procedure for estimating the two parameters, so that the blurred signature can be automatically refocused. The algorithm utilizes optimization of an image domain contrast metric. We present results of refocusing moving targets in real SAR imagery by this method.

1. INTRODUCTION AND PROBLEM STATEMENT

We consider the general problem of imaging a target (typically a vehicle) moving at constant speed in a straight line, with a SAR system that forms imagery collected in the spotlight mode. More specifically, we consider only those cases wherein the relationship between the collected phase history domain data and the formed complex SAR image is simply a Fourier transformation. That is, we will assume that the image resolution and patch size are such that the processing step of polar-to-Cartesian interpolation (also known as *polar reformatting*) of the phase history samples prior to Fourier transformation is not required. As seen by this type of SAR system, a vehicle moving at constant speed in a straight line exhibits three major effects in the formed SAR image: 1) the target is displaced in the cross-range direction by an amount that is proportional to its velocity component in the range direction. This is sometimes referred to as a *Doppler shift*, and its classic demonstration is the image of a railroad train traveling in the range direction appearing displaced in cross-range off of its tracks; 2) the target signature is defocused (blurred) in the cross-range dimension by an amount that depends upon the cross-range component of the target velocity; and 3) the target is imparted a two-dimensional defocus (i.e., in both range and cross-range dimensions), the magnitude of which is determined by the range component of the target velocity. Figure 1(a) shows the SAR collection geometry, while Figure 1(b) indicates the relationship between the collected phase history data and the formed SAR image.

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Figure 1: (a) SAR collection geometry for *spotlight-mode within the beam mode*; (b) Relationship between phase history and formed image domains

As indicated in Figure 1(a), the position of the aircraft along the flight path is described by ξ , and the slant range is r_0 . The angular extent of the synthetic aperture is $\Delta\theta$, while the length of the aperture is A , so that $\Delta\theta = A/r_0$. As shown in Figure 1(b) the phase history data are denoted as $G(X, Y)$, where X and Y are the ground-plane cross-range and range spatial frequencies, respectively. The formed SAR image is described by $g(x, y)$, where x and y denote the ground plane cross-range and range dimensions, respectively. The offset in range spatial frequency in the phase history domain is $Y_0 = \frac{4\pi}{\lambda} \cos \psi$, where ψ is the depression angle of the collection, and λ is the radar wavelength. The extent of the spatial frequencies in the X and Y dimensions are ΔX and ΔY , respectively.

2. DERIVATION OF THE TWO-DIMENSIONAL PHASE FUNCTION FOR A TARGET MOVING WITH CONSTANT VELOCITY

In this section we derive the phase function that is imposed upon a constant velocity moving target imaged by the SAR system described above, by considering separate phase terms for the range and cross-range components of the target velocity vector. The result will be that the phase history of the moving target is multiplied by a two-dimensional phase involving a hyperbolic term XY , which depends upon the range-component of target velocity. In addition, the range-component gives rise to a linear phase in the X dimension that accounts for the *Doppler shift* of the mover. The cross-range component of target velocity will be shown to impose a one-dimensional quadratic phase term in X onto the target phase history. The net effect will be a 2-D function that completely accounts for all of the effects of constant velocity motion of the target, and that is parametrized by the two components of the target velocity.

2.1 THE PHASE TERM IMPOSED BY THE RANGE COMPONENT OF TARGET VELOCITY

The Fourier transform relationship assumed between the image and phase history domains makes the derivation of the phase function for the range component of target velocity fairly simple. Each pulse is transmitted, received, and demodulated at a particular position ξ along the synthetic aperture, yielding one column of Fourier transform (phase history) data for the associated value of spatial frequency X . For the situation in which the target moves with constant speed in the range direction, the target is simply translated in range by a fixed amount from pulse to pulse. A well-known theorem from Fourier transforms dictates that a translation in one domain results in multiplication by a linear phase function in the other domain. Therefore, if on a given pulse the target has moved by amount Δy since the beginning of the collection, the phase history data corresponding to that value of X are given by:

$$G_{vy}(X, Y) = G(X, Y) \exp\{-j\Delta y Y\} \quad (1)$$

where $G(X, Y)$ represents the phase history data for the stationary target. The amount of translation Δy is proportional X , because X is proportional to the platform's position along the aperture, ξ , which in turn is proportional to aperture time. The net result is that each column of phase history data will be multiplied by a linear phase function in Y , the slope of which grows proportionately with aperture position.

The relationship between ξ and X is given by:

$$\xi = \frac{\lambda r_0}{4\pi} X \quad (2)$$

This scaling between aperture position and cross-range spatial frequency can be easily derived by equating two expressions for cross-range image resolution, ρ_x . This gives the ratio of total aperture length A to total X -extent ΔX which is the desired scale factor:

$$\rho_x = \frac{\lambda}{2\Delta\theta} = \frac{2\pi}{\Delta X}$$

Using $\Delta\theta = A/r_0$ we then have that:

$$\frac{A}{\Delta X} = \frac{\xi}{X} = \frac{\lambda r_0}{4\pi}$$

If the target's range component of velocity in the ground plane is v_y and t denotes aperture time, or *slow time*, then:

$$\Delta y = v_y t = v_y \frac{\xi}{v_p} \quad (3)$$

where v_p is the platform speed. We can now complete our derivation of the phase function by inserting the expressions for Δy , and ξ into Equation 1. The result is:

$$G_{vy}(X, Y) = G(X, Y) \exp\left\{-j \frac{v_y \lambda r_0}{v_p 4\pi} XY\right\} \quad (4)$$

Next, consider that the phase history data are offset in the Y dimension by an amount $Y_0 = \frac{4\pi}{\lambda} \cos \psi$. When the Fourier compression is performed, the origin of the data is taken to be at the center of their support, i.e., the data are effectively translated by Y_0 . If we denote the coordinates of these translated spatial frequencies (X', Y') , where $Y' = Y - Y_0$ and $X' = X$, then we have for the moving target phase history:

$$G_{vy}(X, Y' + Y_0) = G(X, Y' + Y_0) \exp\left\{-j \frac{v_y \lambda r_0}{v_p 4\pi} X(Y' + Y_0)\right\} \quad (5)$$

If we denote the translated data as $G'_{mov}(X', Y')$, we have:

$$G'_{vy}(X', Y') = G'(X', Y') \exp\left\{-j \frac{v_y \lambda r_0}{v_p 4\pi} X'Y'\right\} \exp\left\{-j \frac{v_y \lambda r_0}{v_p 4\pi} X'Y_0\right\} \quad (6)$$

The interpretation of the above equation is that the effect of a range component of target velocity is to impose an $X'Y'$ (hyperbolic) phase onto the phase history data, as well as a linear term in X' . The effect of the hyperbolic term will be to blur the image domain data in both range and cross-range dimensions, while the effect of the linear term will be to translate the formed moving target signature in the image cross-range dimension. This latter effect is precisely the *Doppler shift* referred to above. The magnitude of this shift (in meters) will be given by:

$$\begin{aligned} \Delta x_d &= \frac{v_y \lambda r_0}{v_p 4\pi} Y_0 \\ &= \frac{v_y}{v_p} r_0 \cos \psi \\ &= \frac{v_r}{v_p} r_0 \end{aligned} \quad (7)$$

where v_r is the range-component of the mover's velocity in terms of *slant plane range*.

2.2 THE PHASE TERM IMPOSED BY THE CROSS-RANGE COMPONENT OF TARGET VELOCITY

The phase term associated with the cross-range target velocity component is derived in a manner very similar to that of the range component. Analogous to Equation 1, we have:

$$G_{vx}(X', Y') = G(X', Y') \exp\{-j\Delta x X'\} \quad (8)$$

where again $G(X', Y')$ is the phase history of the stationary target. In this case, the amount of cross-range translation of the mover, Δx , as measured from the beginning of the aperture, is given simply by:

$$\Delta x = v_x t = \frac{v_x}{v_p} \xi$$

where v_x is the mover's cross-range velocity component. Using the relationship between ξ and X (Equation 2) we then have (recall that $X = X'$):

$$\Delta x = v_x t = \frac{v_x}{v_p} \frac{\lambda r_0}{4\pi} X' \quad (9)$$

Equation 8 then becomes:

$$G_{vx}(X', Y') = G(X', Y') \exp\{-j \frac{v_x}{v_p} \frac{\lambda r_0}{4\pi} X'^2\} \quad (10)$$

Equation 10 indicates that the effect of cross-range velocity is to impose a quadratic phase term in the X' dimension. This will result in one-dimensional blurring in the azimuthal direction in the image domain.

3 A CONTRAST OPTIMIZATION ALGORITHM FOR ESTIMATION AND CORRECTION OF THE MOVING TARGET PHASE FUNCTION

In this section we propose an algorithm for automatically refocusing a section (chip) of image domain data that is thought to contain the blurred signature of a moving target undergoing constant velocity. This procedure optimizes a measure of contrast for the refocused image segment, wherein contrast is defined as the ratio of the estimated standard deviation to the mean of the image domain data contained in the chip [2]. For each guess at the two components of moving target velocity, the conjugates of the hyperbolic and quadratic phase terms are applied to the Fourier transform of the mover's image chip. Upon inverse Fourier transformation, an estimate of the refocused image chip is produced and a value for the contrast is produced. We then employ Fletcher's method [3] in a search for the values of v_y and v_x that maximize the contrast. When the optimization procedure is complete, we end up with a well-focused image of the moving target, as well as estimates for the two velocity components.

Figure 2(a) shows a 1-meter resolution SAR image of a van moving at roughly mph along the road that runs approximately vertically near the right-hand edge of the scene. Note that the signature of the moving van appears shifted in cross-range to the left edge of the scene. Figure 2(b) shows an enlargement of the moving van signature. It resembles an interference pattern

because the radar reflections from the van are dominated by a pair of corner reflectors placed on the van's roof. In this case, the range component of velocity was sufficiently large to cause a Doppler shift of more than one scene width. That is, the van signature actually *wrapped* several times around the scene width. Figure 3(a) shows the result of chipping out the blurred van signature and applying to it the contrast optimization technique for refocus. Note that the algorithm produced two separable point targets, which are in fact the corner reflectors on the van roof. An enlargement of these corners is shown in Figure 3(b). In Figure 4, we have taken the range velocity estimate from the refocus algorithm and used it to compute the Doppler shift of the moving van (see Equation 7). Note that the van is in fact correctly repositioned on the road. A second example of refocusing moving targets in real SAR imagery is shown in Figure 5. Figure 5(a) shows the blurred signatures from two moving trucks. Figure 5(b) is the output of the contrast optimization refocus algorithm. The focus of the track signatures has been substantially sharpened.

4 SUMMARY AND CONCLUSION

We have demonstrated that a successful moving target refocus algorithm for constant velocity moving targets in SAR imagery can be developed by construction of a phase function for the Fourier domain of the image (phase history domain) that contains a hyperbolic term (XY) for the range component of the mover's velocity, and a quadratic term (X^2) for the mover's cross-range velocity component. By maximizing a contrast function wherein the free parameters are v_y and v_x , we can refocus the image chip containing the mover signature to obtain the signature of the stationary vehicle. Also, the estimated range velocity can be employed to calculate the Doppler shift, and the refocused moving target can be properly repositioned in the scene, e.g., a vehicle can be placed back on the road.

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(a)

(b)

Figure 2: (a) SAR image of moving van. Note blurred signature of moving van in lower left corner of image. The van with two corner reflectors on its roof is actually moving along the road running approximately vertically on the right side of the scene. Due to the Doppler shift, the signature of the van appears shifted in cross-range, to the left edge of the scene. (b) Enlargement of the moving van signature. The extensive two-dimensional blur is due to the hyperbolic phase term injected by the range component of velocity, as described above. The interference pattern in this case comes from the interaction of the two strong corner reflectors on the roof of the van.

(a)

(b)

Figure 3: (a) The moving van chip has been refocused by the contrast optimization scheme and has been placed back where the Doppler shift left the blurred signature. (b) Enlargement of the refocused van, showing that the two corner reflectors on the roof are now well-focused and can be resolved.

Figure 4: SAR image showing blurred moving van signature (lower left) and refocused van signature properly placed back on road. The Doppler shift to place the van in its proper position on the road is derived from the estimated range velocity component in the contrast optimization algorithm.

(a)

(b)

Figure 5: (a) SAR image of two moving trucks showing two-dimensional blur. (b) Trucks refocused using contrast optimization algorithm.

6. ACKNOWLEDGMENTS

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