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TWO-DIMENSIONAL IMAGING OF MOVING TARGETS IN SAR DATA

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ABSTRACT

Digital processing algorithms for two-dimensional fine-resolution imaging of moving targets in synthetic aperture radar (SAR) data are described. The targets may have any translational and rotational motion relative to the data collection platform. Initially, an efficient spatially invariant focusing algorithm, shear averaging, is used for preliminary focusing of the target data. Then target motion is estimated from tracks of prominent points. Appropriate phase compensation and data formatting operations eliminate the motion-induced degradations of the SAR target signatures. Four target prominent points are required for estimation of three-dimensional motion, but limited motion estimation can be accomplished with fewer. Final image quality is dependent upon the nature of the target motion and upon the purity of the prominent points.

INTRODUCTION

Basic SAR Imaging

Synthetic aperture radar (SAR) is an active, coherent, all-weather imaging system which operates in the microwave region of the electromagnetic spectrum. In SAR imaging relative rotation between the SAR antenna and the target is necessary; either the target may rotate or the antenna may move. The antenna transmits a series of radar pulses and receives the reflected energy from the targets. The time delays with which the returns are received provides differentiating information about target ranges. Target cross-range or angle positions are derived from the pulse-to-pulse changes in range (range rate).

Under the simplifying assumptions that the radar antenna is far from the target relative to the size of the target, and that the received radar data are processed over a small time interval, the relationships between the location of a target point, x_o, y_o, and the target range, $r(t)$, can be shown to be [1]: (Figure 1)

$$r(t) = r_a + y_o \qquad (1)$$

$$\frac{dr(t)}{dt} = \omega x_o \qquad (2)$$

where r_a is the distance from the radar antenna to the scene center, and
ω is the relative rotation rate.

Fine range resolution is obtained by transmission of a wide bandwidth signal, such as a linear frequency modulated (F.M.) signal or a long-coded pulse, whereas fine azimuth resolution results from processing pulses over a wide aspect.

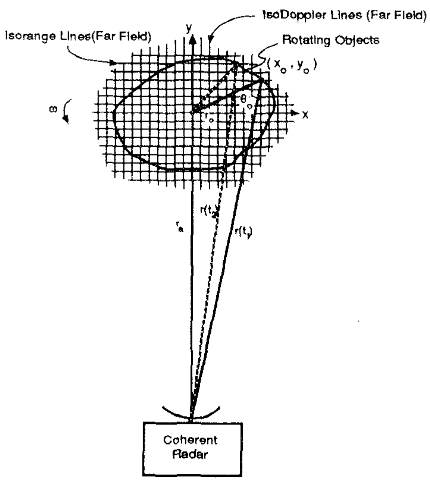

Figure 1: Simple SAR Imaging Model.

In many interesting SAR imaging scenarios, the range from the radar antenna to the scene center is a function of time, $r_a(t)$, and the relative rotation rate between the antenna and target is also a function of time, $\omega(t)$. One such case is provided by a form of airborne terrain mapping, called spotlight radar; the antenna illuminates a fixed area on the ground from a continuously changing look angle (Figure 2).

Accurate imaging requires knowledge of r_a and of ω. In normal SAR imaging of stationary scenes, such as spotlight imaging, the requisite knowledge of $r_a(t)$ and $\omega(t)$ is provided by an inertial navigation system (INS) associated with the antenna. In the case of a stationary radar imaging a rotating object, $r_a(t)$ and $\omega(t)$ are known a priori or must be estimated from the radar data. In yet another variation of SAR imaging,

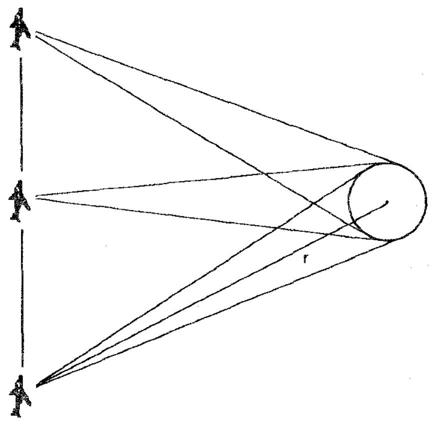

Figure 2: Spotlight SAR.

the relative motion is provided both by a known movement of the antenna and an unknown movement of the target. This scenario frequently occurs during stationary scene imaging when a target moves through the scene during the data collection.

SAR Processing

Although our introductory discussion of SAR imaging centered upon a two-dimensional imaging model, in general, the relative motion between the target and platform is three-dimensional as well as time-varying in nature. In order to limit the following discussion, we assume that we are imaging a moving target with either a spotlight SAR or with a stationary inverse SAR (ISAR) and that we are imaging at far range. We also assume that the relative motion between the platform and target is unknown and must be estimated from the radar data. Furthermore, the desired resolution of the image is fine enough that target points on the object may move through several resolution cells during the required processing time; this motion through resolution cell problem must be compensated in order to form high quality images.

There are a plethora of techniques for processing SAR data into images (see reference [1] for an overview). They vary according to the approximations and assumptions made, processing speed and shortcuts, etc. The block diagram in Figure 3 illustrates a typical processing sequence for spotlight SAR data of a stationary scene. Linear frequency modulation (FM) waveforms are used in order to obtain fine range resolution. The first step is to remove the effects of the gross range changes to the scene center for each pulse by multiplying each returned signal with a replica of the transmitted signal which is delayed by precisely the round-trip delay to scene center; INS information is used to compute the delays. After this mixing operation, a signal from a single point scatterer is of a single frequency and starting phase which are proportional to the range of the scatterer. After digitization of the data, the motion-compensation, which has mostly been done in the mixing operation, is fine-tuned using measurements or estimates of the relative

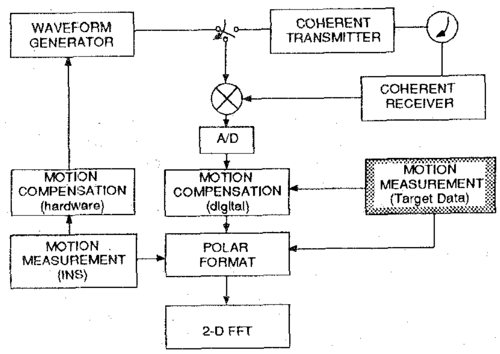

Figure 3: Simplistic Processing Scheme for Spotlight SAR.

motion. The motion information is used to lay the collected pulses in a polar format, corresponding to their look directions during data collection (Figure 4); polar formatting with accurate look directions corrects for the previously mentioned motion through resolution cell problem [2]. In two-dimensional imaging, the data are projected onto an imaging plane, usually the ground plane. Interpolation is used so that the resulting output of these operations is a downsampled and corrected version of the original data. A two-dimensional inverse Fourier transform is performed to obtain an image. In principle, there is no difference between processing stationary scene data and processing moving target data. In the former case, the requisite motion information is provided by INS data. In the latter case, it is estimated from the radar data. In both cases, the relative motion must be known with an accuracy of a fraction of a wavelength.

EFFECTS OF UNCOMPENSATED MOTION ON IMAGES

When targets are moving with unknown and uncompensated motion during the data collection, the SAR target signatures are typically mislocated and smeared out in azimuth due to phase errors induced by the motion. The specific effects of target motion on SAR signatures and the effectiveness of any motion estimation and correction algorithms depend strongly upon the kind of motion.

Rigid body translation causes spatially invariant phase errors and smearing (all points on the target are smeared the same way). If the translation is sinusoidal, the target signature may split into paired echos or ghosts. Wide bandwidth or random phase errors cause extensive signature smearing.

Rigid body rotation can complicate the basic shape of the SAR target image. If the rotation is confined to the imaging plane (i.e., if the axis of rotation is perpendicular to the line of sight) and does not change direction, the target signature is distorted in azimuth due to unknown azimuth resolution from the target's rotation. If such rotation is nonuniform, then the target signature suffers spatially variant smearing. In principle, it is possible to obtain a completely focused two-dimensional image in such cases, as will be discussed later.

Rotation outside the imaging plane causes primarily perspective distortion and height-of-focus smearing. A stationary target signature appears projected on the nominal slant range plane, which is the plane normal to the radar-to-target rotation axis. If the target rotation also has a component around the axis parallel to the antenna flight path, then this imaging plane tilts away from the nominal imaging plane, and the target signature, which is projected onto this tilted plane, appears distorted. Rotational components outside the nominal slant range plane can lead to a height-dependent (height is the distance from the imaging plane of a specified point of the target) smearing. It is not possible to eliminate height-of-focus smearing using two-dimensional imaging techniques; a three-dimensional imaging procedure is required [2].

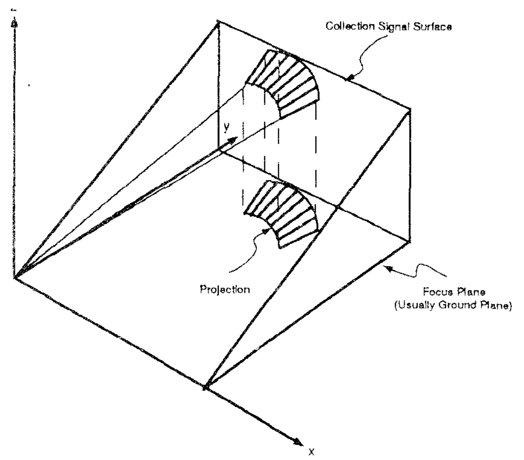

Figure 4: Polar Format Signal Projections in Frequency Domain.

ESTIMATION OF UNKNOWN TARGET MOTION

Estimation of unknown target motion from radar data is a difficult task. A fundamental limitation is that not all components of target motion are observable by a range-only sensor, such as a radar. Only motions involving pulse-to-pulse changes in range from the antenna to the target points are observable. Another difficulty arises from the combination of the motion-induced smearing of the target signature with background clutter; the signal-to-background ratio is frequently poor. Although complete knowledge of target motion is not necessarily required in order to obtain a fine resolution image, complete knowledge of observable target motion is necessary in order obtain the best possible two-dimensional image and to predict the quality of that image. In practice, target motion estimation is not done with a single algorithm, but with a combination of algorithms with complementary capabilities. The most powerful estimation algorithms, which provide information about target rotations, rely upon accurate estimation of target dominant scatterers at each pulse. Such algorithms do not typically perform well under poor signal-to-background conditions. On the other hand, algorithms which do perform well under these conditions provide very limited information about motion.

Translational Motion Estimation

Many algorithms provide estimates of pulse-to-pulse changes in range from an antenna to a moving target. Dominant scatterer algorithms provide this data via the measured frequencies and phases of a prominent point [3, 4]. Other algorithms also provide phase error estimates for the target radar data [5, 6, 7, 8, 9]. Dominant scatterer algorithms can provide very accurate phase error estimates, but require the identification and isolation of a target prominent point. Some phase error estimation algorithms also require that the target image be characterized by some specific structure [6]. Other algorithms are limited in that they are capable of estimating only low frequency phase errors [3, 5]. Some algorithms provide reasonable estimates only of relatively small phase errors [9].

Uncompensated translational motion often results in target signatures that are degraded by large and/or high frequency phase errors. Thus, we initially apply an efficient algorithm which is capable of estimating these phase errors [7, 8]. This algorithm, called shear averaging, is automatic, noniterative, and very fast. There are no requirements for a specific kind of target structure, such as prominent points.

The shear averaging algorithm was inspired by the analogy between speckle interferometry and the SAR focusing problem. It is modeled after the Knox-Thompson algorithm and is closely related to optical shearing interferometry. Let $G(v, u)$ be the corrupted SAR signal history, which can be represented as the product of the ideal signal history and a one-dimensional azimuthal phase error:

$$G(v, u) = F(v, u) \exp\left[j\phi_e(u)\right]. \tag{3}$$

The shear average is

$$S(u) = \sum_{v=1}^{N} G(v, u) G^*(v, u - a) \tag{4}$$

where a is the shift index, typically one pulse.

The shear average can be written as:

$$S(u) = \exp\left[j\phi_e(u) - j\phi_e(u - a)\right] \sum_{v=1}^{N} F(v, u) F^*(v, u - a). \tag{5}$$

The Fourier transform of the target's reflectivity may be viewed as a realization of an ergodic random process. Thus, the quantity $\Sigma F(v, u)F^*(v, u - a)$ is proportional to an ensemble average which can be recognized as a sample of the far-field mutual intensity function if the target were incoherently illuminated. By the van Cittert-Zernike theorem [10], this mutual intensity is the Fourier transform of the incoherently illuminated object. Using the normalized mutual intensity or complex coherence factor, μ, S(u) can be expressed as:

$$S(u) = \exp\,[j\phi_e(u) - j\phi_e(u - a)]NI\mu(o, a) \quad (6)$$

where I is the average intensity.

Thus, the SAR phase error can be computed recursively by integrating the phase of the shear average, S(u).

It can be shown that the standard deviation of the phase error estimated in this way is approximately given by:

$$\sigma_{\phi_e} = \frac{1}{|\mu(o, a)|}\sqrt{\frac{M}{2N}} \quad (7)$$

Here, N is the number of independent range samples in the average and M is the number of independent azimuth samples. This standard deviation can range from a fraction of a radian to several radians, depending upon the orientation, size, and shape of the target signature. Thus, a significant residual smear will probably remain in the corrected image. Furthermore, the phase error estimate for moving targets is underestimated due to the fact that the moving target data are superimposed upon clutter data. However, we use the shear averaging algorithm primarily to remove gross degradations resulting from translational motion and thus to enhance target signal-to-background ratio so that more elaborate motion estimation algorithms can then be successfully used. An example of a synthetic SAR moving target signature and its shear-averaged correction is shown in Figure 5.

Any residual translational motion between the target and antenna is estimated from a single prominent point which is located precisely in each pulse using Prony line spectrum estimation techniques, and then linked across all the pulses using a linear programming algorithm. The frequencies and phases of the prominent point across the aperture provide an accurate measure of the differences in range between the stationary scene center and the moving point at each pulse. This information is used in a conventional motion compensation procedure to make this prominent point effectively the new center of the scene. An example of a synthetic moving target signature from which all translational motion has been removed in this manner is shown in Figure 6.

Rotational Motion Estimation

For the case of a rotating target, elimination of translational motion effects by using spatially invariant focusing procedures, as described above, is not sufficient in order to obtain a

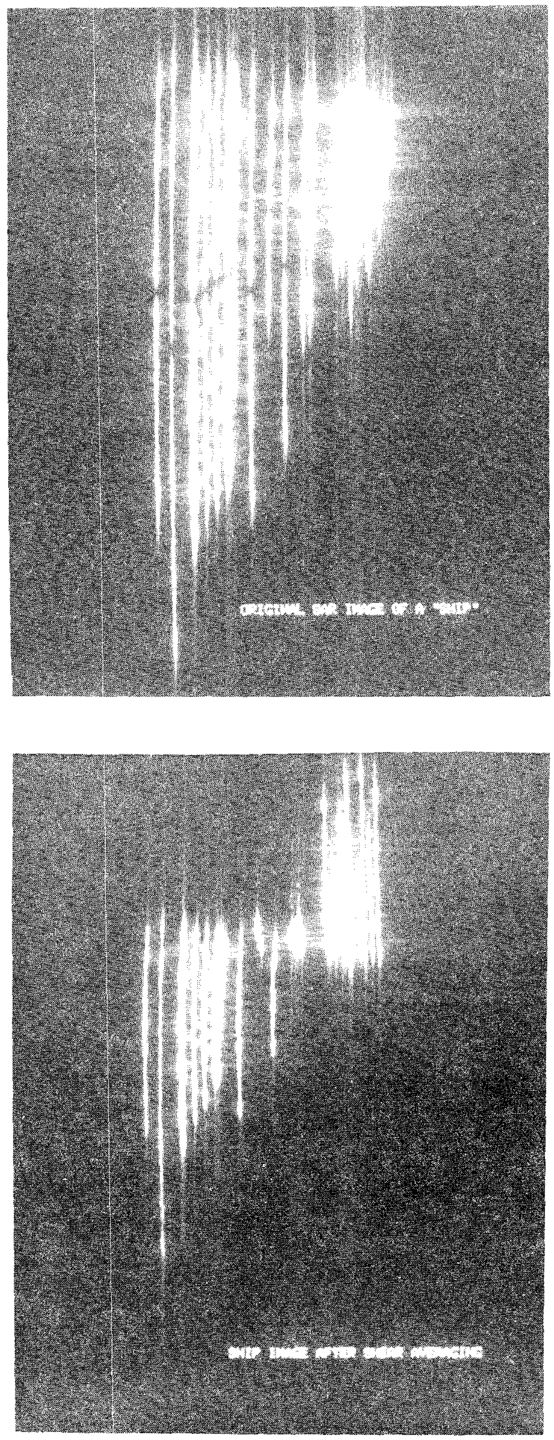

Figure 5: Synthetic SAR Target With Planar Motion -
- (Top) Original Target Image
- (Bottom) After Shear Averaging.

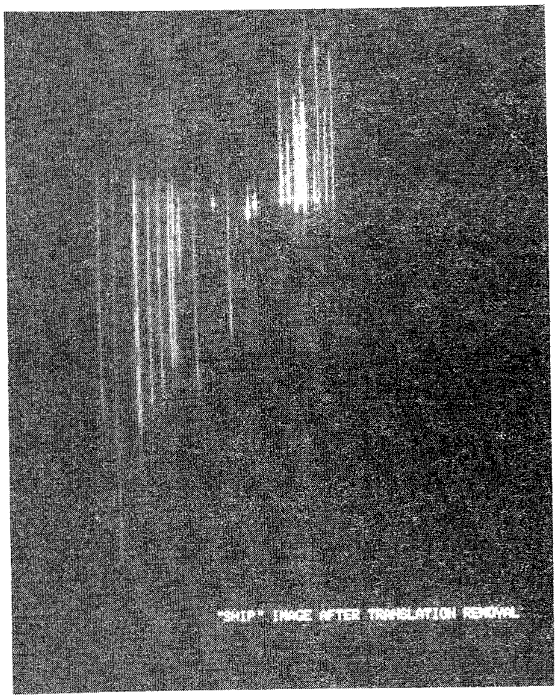

Figure 6: Synthetic Target Image After Correction For Translational Motion

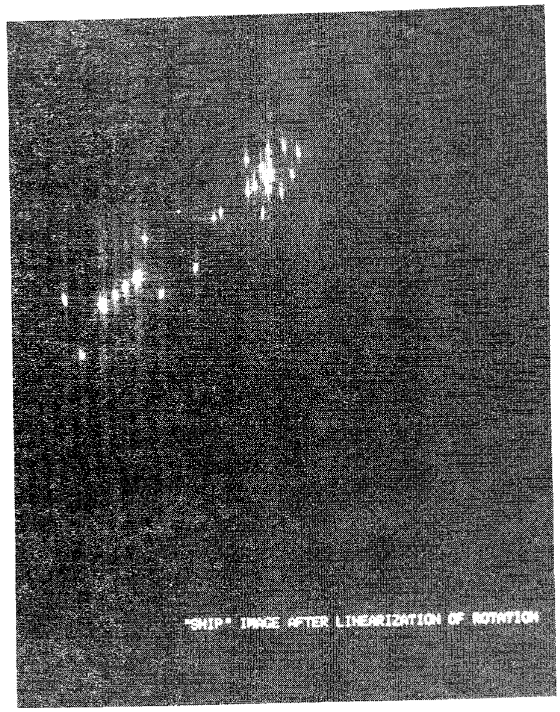

Figure 7: Synthetic Target Image After Linearization of Rotation.

satisfactorily focused target image whose dimensions in azimuth are known. Algorithms for estimating rotation of targets in general must be spatially variant. We describe two general approaches to the problem of estimating rotation of targets in SAR data. These approaches are based upon the accurate estimation and tracking of target dominant scatterers. Although estimation of target motion through tracks of prominent points is a nontrivial accomplishment, the most powerful motion analysis procedures require prominent point data.

After a first target prominent point has been used as mentioned above to estimate and compensate for any residual target translational motion, a second target prominent point can be used to estimate the relative rotation of the target to within a scale factor [11]. If the processing algorithm assumes that the signal history pulses are evenly spaced in angle when, in fact, rotation is nonuniform, nonlinear phase errors and subsequent spatially variant image domain smearing will result. The unwrapped phase of this second dominant scatterer is proportional to the target's relative rotation rate and is used in recomputing appropriate azimuth positions for the pulses in order for target rotation to appear to be effectively constant. Figure 7 illustrates the synthetic moving target image after spatially variant smearing has been removed by linearizing the relative rotation. The effective focusing plane for the target image is determined by the first prominent point which was used for estimation of translational motion, the second prominent point, and the location of the radar antenna at the center of the aperture.

In order to obtain a measure of the proper polar formatting angular scale and to achieve correct azimuth dimensioning of the target image, more than two dominant scatterers are required. The angular spacing between the pulses for polar formatting must be measured because the target has contributed an unknown amount to the total relative rotation between the radar platform and target. If the target's rotation occurs almost entirely in the nominal slant range plane, then a third prominent point is sufficient in order to obtain this measurement. The quadratic component of the unwrapped phase of this point provides an estimate of this angular spacing. The motion of the previous synthetic target was confined to the slant range plane. The properly polar formatted version of the image is shown in Figure 8.

If the target's rotation occurs primarily in a plane other than the nominal slant range plane or if the target has a varying rotational axis during the data collection, then the phase-error method mentioned above does not result in an accurate measure of the angular scale. To make matters worse, one generally has no reliable way of determining whether the rotation occurs primarily in this plane or not, unless a priori information is available; thus, the phase error method for measuring the polar formatting scale factor cannot be trusted.

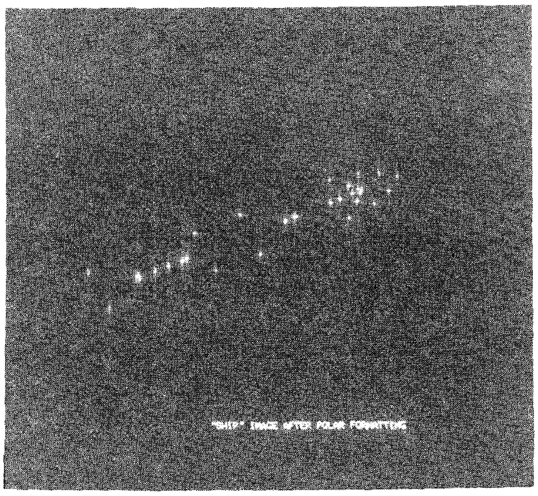

Figure 8: Synthetic Target Image After Appropriate Polar Formatting.

An approach for measuring all target motion that is observable by a range-only sensor, such as a radar, has been developed [12]. This technique requires four accurate tracks of range measurements from four prominent points of the moving target. A fundamental assumption is that the four prominent point tracks correspond to four scatterers on a rigid body. The main idea underlying this comprehensive motion measuring method is that because the observed target is a rigid body, there are constraints imposed upon the realm of possibilities for the observed differences in range to any two of the target points. These limitations can be mathematically expressed in the form of an invariant equation containing both observed range differences and unknown invariant parameters. Because the invariant parameters enter the equation linearly, they may be estimated via least squares techniques. From the invariant parameter estimates, all details concerning the Euclidean geometry of the underlying points on the moving object may be determined. More specifically, the distances between the target points may be computed. Thus, it is possible to determine the shape of a target without having to form an image of it. From the derived shape vectors, one can then compute the look direction vectors for each pulse of data. This look direction history contains all the information that can possibly be extracted by any method concerning the relative rotational motions between the target and radar platform.

An example of such an invariant equation for the range tracks of four non-coplanar points on a rigid body moving with three-dimensional motion is given by the following:

$$
\begin{aligned}
& I_1\left[r_1(t) - r_o(t)\right]^2 + I_2\left[r_2(t) - r_o(t)\right]^2 \\
& + I_3\left[r_3(t) - r_o(t)\right]^2 + J_3\left[r_1(t) - r_o(t)\right]\left[r_2(t) - r_o(t)\right] \\
& + J_2\left[r_1(t) - r_o(t)\right]\left[r_3(t) - r_o(t)\right] \\
& + J_1\left[r_2(t) - r_o(t)\right]\left[r_3(t) - r_o(t)\right] = 1
\end{aligned}
\tag{8}
$$

Here, the $r_k(t)$ are the measured ranges to point k, and the Is and Js are the invariant parameters to be estimated. These invariant parameters all have geometric interpretations. For example, I_1 is the square of twice the area of the triangle formed by the points P_2, P_3, and P_o divided by the square of six times the volume of the tetrahedron formed by the four points.

The derived look direction history is essentially the estimated substitute for the INS data which is normally available for SAR image formation processing of stationary scenes. Thus, the formation of the moving target image may proceed just as in the conventional scenario. It is also possible to determine a "best" imaging plane for the moving target data by determining the plane in which most of the target rotation has occurred. In this way, one may more reliably choose an imaging plane which results in the highest possible target image quality than by indirectly selecting an imaging plane by the arbitrary selection of the first and second prominent points. Figure 9 illustrates a very simple synthetic target with nonplanar motion. The figure shows the conventionally processed image, the image which has been focused using the first prominent point technique described above, and the image which has been focused using invariant analysis methods. It should be noted that the invariant analysis methods resulted in the selection of a more appropriate imaging plane so that the target image is less degraded by residual smearing than the target image focused by the first method.

SUMMARY

Techniques for obtaining focused two-dimensional SAR images of moving targets have been described. The imaging strategy consists of 1) estimating and removing the effects of gross translational motion and enhancing the target signal-to-background level with a fast efficient phase-error estimating algorithm, shear averaging, so that 2) prominent points of the target signature can be used to provide information about the target's rotation. The estimates of target motion which have been entirely estimated from data are then used in conventional SAR processing algorithms to obtain a focused target image.

Ongoing research is heavily concerned with development of accurate and automatic prominent point estimation and tracking techniques, development of optimal imaging strategies, and analysis of the limitations in image quality arising from various kinds of motions.

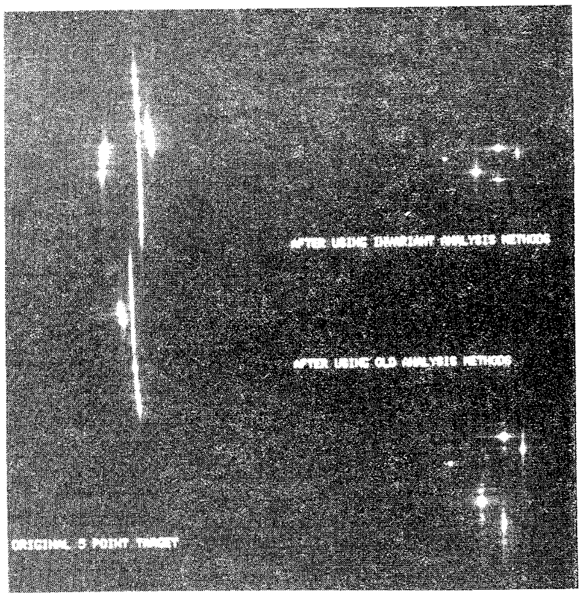

Figure 9: Synthetic Target With Nonplanar Rotation -
- (Left) Original Image
- (Right-top) Image Focused With Invariant Analysis Method
- (Right-bottom) Image Focused With First Prominent Point Technique.

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