RADAR IMAGING OF GROUND MOVING TARGETS

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Abstract—In this paper, we analyze the effect of target motion on synthetic aperture radar image and discuss how a multi-aperture radar can detect, focus and relocate moving targets in clutter. AN/APY-6 radar data is used for analyzing radar imaging of ground moving targets. Some applications of the time-frequency transform to detect and focus moving targets are also discussed.

I. INTRODUCTION

A synthetic aperture radar (SAR) image is a high-resolution map of surface target areas and terrain in the range and the azimuth dimension. If there are moving targets in the scene, SAR cannot simultaneously produce clear images of stationary targets as well as clear images of moving targets. Moving targets appear as defocused and spatially displaced objects superimposed on the SAR map. In these cases, an important issue is the ability to detect and clearly image moving targets in SAR.

There are three basic steps for SAR imaging of moving targets. The first step is to detect moving targets in clutter; the second step is to focus images of moving targets; and the third step is to re-locate the detected moving targets into their true location in the SAR scene.

Moving target indication (MTI) is a function of detecting moving targets in clutter. With the MTI, radar returns from terrain and stationary objects can be suppressed; only the returns from moving targets are used for the reconstruction of radar images. There are many algorithms for focusing the image of detected moving targets. Because of additional Doppler caused by target motion, the detected and focused target is not necessarily located in its true location in the SAR image. To re-locate the detected target to its true location, an antenna array or multiple antenna SAR with independent processing channels is often used.

When the radar platform is moving along the azimuth direction at an altitude of h, and when a point target at range $R_0$ is moving with a velocity $v_x$ in the radial direction, and a velocity $v_y$ and an acceleration $a_y$ in the azimuth direction as shown in Fig.1, then the Doppler frequency shift of the returned signal from the target consists of two parts [1,2]

$$f_D = f_D_{\text{Radar}} + f_D_{\text{Target}}$$

where the Doppler shift due to the radar motion is

$$f_D_{\text{Radar}} = \frac{2}{\lambda} \frac{x_0 v_x}{R_0} + \frac{2 v_x^2}{\lambda R_0}$$

and the Doppler shift due to the target motion is

$$f_D_{\text{Target}} = -\frac{2}{\lambda} \frac{x_0 v_x + y_0 v_y}{R_0}$$

$$+ \frac{2 v_y^2 + v_x^2 + x_0 a_x + y_0 a_y - 2 v_x v_y}{\lambda R_0}$$

For a stationary target, according to (1), its Doppler shift is induced only by the radar motion. The Doppler shift consists of two parts: the Doppler centroid

$$f_D_{\text{Target}} = -\frac{2}{\lambda} \frac{x_0 v_x}{R_0}$$

and the Doppler rate

$$f_D_{\text{Target}_R} = \frac{2}{\lambda} \frac{v_x}{R_0}$$

Given a radar velocity $v$ and an initial range from the radar to the target $R_0$, the Doppler centroid of the stationary target is determined only by its location in the azimuth direction $x_0$. After azimuth compression, the Doppler rate can be compensated, and the image of the stationary target becomes focused.

However, for a moving target, according to (2) its Doppler centroid is determined not only by its geometric location $(x_0,y_0)$, but also by its velocity $(v_x,v_y)$. The Doppler drift of the moving target becomes

$$f_D_{\text{Target}_C} = \frac{2}{\lambda} \frac{x_0 v_x + y_0 v_y}{R_0}$$

and its Doppler rate becomes

$$f_D_{\text{Target}_R} = \frac{2}{\lambda} \frac{v_x^2 + v_y^2 + x_0 a_x + y_0 a_y - 2 v_x v_y}{R_0}$$

Given a radar velocity $v$ and an initial range from the radar to the target $R_0$, the Doppler rate of the moving target is determined not only by its geometric location $(x_0,y_0)$ but also by its velocity and acceleration. If the Doppler rate cannot be compensated, then the image of the moving target becomes defocused.

II. THE EFFECT OF TARGET MOTION ON SAR IMAGE
(5) and (6) tell us that the quadratic phase variation between the target and the radar causes de-focusing of the moving target’s image. Usually, while stationary targets are well focused with a reference function that is a replica of the signature of a stationary target, the image of a moving target may become de-focused and also shifted in the cross-range dimension. If its Doppler rate \( f_{\text{Doppler}} \) can be well compensated, then the image of the moving target may be re-focused, but the image of stationary targets becomes de-focused.

In SAR imagery, the geometric location of a moving target may be shifted from its true location in the azimuth direction. An image of the moving target may be smeared in the azimuth direction if the target has azimuth motion, and smeared in the radial direction if it has range walk.

When the target moves only in the radial direction, i.e., \( v_x = 0; v_y \neq 0 \), then the image shift in the azimuth direction is determined only by target’s radial velocity \( v_y \). If the target has only azimuth motion, i.e., \( v_x \neq 0; v_y = 0 \), the image shift in the azimuth direction, determined by a small value \((x_0/R_0)v_y\), is negligible. However, in both cases the image of the moving target is de-focused in the azimuth direction. Range walk can also cause image smearing in the radial direction.

To analyze the effect of motion parameters on the image of a moving target, i.e., the problem of image smearing and mis-location, we discuss a special case where \( x_0 = 0 \) and \( a_x = a_y = 0 \). If we know the Doppler centroid and the Doppler rate exactly, then the velocity \((v_x, v_y)\) of the moving target can be calculated from the above equations (5) and (6). There are several methods for calculating the Doppler centroid and the Doppler rate. But there is no simple approach to obtain exact Doppler centroid and Doppler rate.

However, in general cases where \( x_0 \neq 0 \), the Doppler centroid and the Doppler rate of a moving target is determined not only by its velocity \((v_x, v_y)\) but also by its initial location \((x_0, y_0)\). Therefore, the velocity of a moving target cannot be estimated, and the mis-location problem may not be solved. To estimate the target’s velocities and relocate mis-located moving targets, a multiple aperture or channel SAR imaging system is needed.

III. MULTI-APERTURE SAR IMAGING OF GROUND MOVING TARGETS

To estimate the target’s velocities and relocate mis-located moving targets, multiple-antenna (such as interferometry, planar apertures, or antenna array) is desired. Having multiple antennas with independent receive channels, the displaced phase center antenna (DPCA) technique or the space-time adaptive processing (STAP) technique can be applied to suppress clutter.

Ground moving target indicator (GMTI) is designed to reject radar returns from clutter to detect moving targets. There are several multiple-antenna techniques to perform GMTI. The antenna array may be either along the flight track such as in the Joint STARS [3], which is an electronically-scanned side-looking airborne radar, or a scanned planar array mounted on the nose of an airplane such as the AN/APY-6 radar developed by Northrop Grumman Norden Systems [4]. The AN/APY-6 is a three-port interferometric radar and compared with the conventional monopulse radar, the interferometric radar provides a low sidelobe radiation pattern.

The AN/APY-6 radar is a new generation of the precision surveillance and targeting (PS&T) radar operating at X-band and designed for use in the littoral area. The antenna of the AN/APY-6 radar is a mechanically scanned four-aperture planar array antenna. One larger aperture is used for transmitting waveforms for SAR and GMTI as well as for receiving radar returns for SAR. The three smaller apertures are used for GMTI receive only channels[4]. The APY-6 radar also has capability for moving target imaging (MTIm) and generates high-resolution image of slow moving targets.

Because the image of a moving target may be shifted in the azimuth direction, if we can estimate the amount of shift, the true location of the target can be recovered. Two-port interferometry is able to estimate the target azimuth position and relocate the target to its true location. Yadin [5] indicated that the target angular location could be estimated by the differential phase of two interferometric channels, \( \Delta \phi = \frac{2\pi D}{\lambda} \Delta a \), where \( D \) is the spacing between the two receiving antennas, and \( I_R \) and \( I_L \) are the received signals of the right-channel and the left-channel, respectively. Actually, the differential phase in the two receivers can be derived as

\[
\Delta \Phi = \frac{2\pi D}{\lambda} \frac{\Delta a}{R_0} \Delta \text{shift} \tag{7}
\]

where \( \Delta a \) is the cross-range resolution of the image and \( \Delta \text{shift} \) is the amount of shift in the cross-range of the image. Thus, if we can measure the differential phase \( \Delta \Phi \), the amount of the shift \( \Delta \text{shift} \) can be estimated by

\[
\Delta \text{shift} = \frac{\lambda}{2\pi D} \frac{R_0}{\Delta a} \Delta \Phi \tag{8}
\]

The AN/APY-6 uses three-port STAP clutter suppression interferometry to simultaneously cancel clutter and determine the true azimuth location of the detected target. The true location of the detected target is calculated using the interferometric phase, which is the phase difference between the phase residue of the left interferometric channel and the one of the right interferometric channel. The interferometric phase is linearly proportional to the azimuth location of the target as indicated in (8). By comparing the estimated azimuth location to the Doppler of the target, the offset of the Doppler can be measured. The offset is used to correct the azimuth location of the target as described in [7]. After
detecting and locating the target, the image of the target can also be focused.

We use APY-6 radar data, including MTIm of a sport utility vehicle (SUV) and SAR GMTI images with ground movers, provided by Northrop Grumman Norden Systems to analyze SAR imaging of ground moving targets and to evaluate the result of the GMTI and MTIm.

IV. ANALYSIS OF AN/APY-6 GROUND MOVING TARGET DATA

Figure 2 shows MTIm imaging of a sport utility vehicle (SUV) while the vehicle is moving. The SUV is shown in Figure 2(a) and includes a corner reflector on the top of the SUV. Range alignment processing for this data is based on the consistent high returns coming from the corner reflector. The radar located on a roof-top in Figure 2(b) is an X-band radar with high resolution imaging capability. The SUV is moving around a circle with a speed of 4 m/sec as illustrated in Figure 2(c).

The radar data is composed of 60 range cells and 2048 pulses. Figure 3(a) presents the range profiles of the data. We select a portion of the data with 256 pulses as shown in Figure 3(b) to generate the image of the SUV. Figure 4(a) is the result of image formation by applying Fourier transform along pulses at each of the range cells. Because the rotation of the SUV causes range walk and varying Doppler of individual scatterers, the image is smeared in both the cross-range and the range domain. To generate a focused image more sophisticated algorithms for individual scatterers, such as polar reformatting, are needed. Polar reformatting can correct the blurring effects of rotational motion for individual scatterers. Polar reformatting reconstructs an image from data surfaces formed in Fourier space based on the rotational motion of the target. It requires re-sampling the data such that the sample points that lie on a polar sampling grid are conformed to the desired sample points on a rectangular sampling grid. To perform polar reformatting, some initial kinematic parameters of the target are required.

Here, we discuss an image formation technique that uses a time-frequency transform to replace the Fourier transform. The advantage of using this technique is that it provides image processing where the restrictions of the Fourier transform can be circumvented [8]. It overcomes these restrictions by providing the time varying Doppler characteristics for scatterers on the target. With a high-resolution time-frequency transform, the image smearing caused by time-varying frequency shifts and range walk can be mitigated without applying sophisticated algorithms. The result of applying the time-frequency transform to the MTIm data is shown in Figure 4(b). By applying the time-frequency based algorithm, clearly well focused SUV images can be seen.

Figure 5 shows a SAR image generated by APY-6 radar data without GMTI. We analyzed three small regions showing smeared structures along the cross-range direction. The region no.1 is located within range cells from no. 901 to no.964. The region no.2 is from no.651 to no.714, and the region no.3 is from no.1201 to no.1264. Figure 6(a) shows the range profiles of region no.1.

After focusing with phase correction, the image of the target in the region no.1 is formed as shown in Figure 6(b). To further analyze the target, let us take a small area around the target with 30 range cells and 100 cross-range cells. Range profiles that correspond to the small area are shown in Figure 7(a). We analyze 100 pulses at range cell no.18, and the time-frequency signature is shown in Figure 7(b), where a ramped time-frequency signature indicates that the target is moving. We have the same result for the target in the region no.2. The above two targets are all moving targets. For the region no.3, we have the corresponding range profiles shown in Figure 8(a) and the time-frequency signature in Figure 8(b), where a flat time-frequency characteristic means the target is stationary. This demonstrates that Time-frequency signatures can be used to distinguish moving targets from stationary targets. Thus, it helps in the detection of moving targets. However, without data in GMTI channels, it is impossible to relocate moving targets to their true locations. [6] discusses how to relocate multiple moving targets with multiple antennas.

SUMMARY

Synthetic aperture radar images of ground moving targets are usually smeared and spatially displaced. We analyzed the effect of target's motion on radar image. We applied time-frequency processing to focus MTIm images and time-frequency analysis to distinguish moving targets from stationary targets.

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REFERENCES


Figure 1. Geometry of SAR and a moving target.

Figure 2. Geometry of MTIm imaging of a SUV.

Figure 3. Range profiles of the SUV data.
Figure 4. Radar image of the SUV: (a) using the Fourier transform, and (b) focused by using the time-frequency transform.

Figure 5. SAR image generated by APY-6 radar data.
Figure 6. (a) Range profiles and (b) image of the target in region no.1.

Figure 7. Time-frequency signature of the target in region no.1.

Figure 8. Time-frequency signature of the target in region no.3.