

High Resolution Millimeter Wave SAR for Moving Target Indication

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Abstract

Synthetic aperture radar (SAR) is an imaging radar technique that provides mapping of static ground scenes. Some existing and forthcoming SAR systems thereby provide very high resolution in the centimeter domain. While high azimuth resolution is achieved by signal processing techniques, range resolution for a traditional frequency modulated system is solely dependent on the signal bandwidth. For millimeter wave (mmW) SAR, operating at frequencies roughly between 30 and 100 GHz, a signal bandwidth of several hundred megahertz or even in the range of gigahertz is achievable. While mmW SAR is generally well suited for ground moving target indication (GMTI), especially at very slow radial target speeds, higher speeds may cause effects that not only displace moving targets but smear and defocus them considerably if not letting them disappear at all. This makes it difficult for GMTI algorithms to detect such targets. Additionally, smearing and defocus are more severe and disturbing at higher resolutions. We analyze the conditions where mmW SAR GMTI works fine and show simulated and real examples of moving targets at 35 GHz and compare them to L-band SAR data.

1 Introduction

The theory of ground moving target indication with SAR has long been known [1]. Many aspects thereof have been analyzed with focus on diverse topics such as sea current measurements from space [2], moving target detection in foliage [3], or the influence of target acceleration on velocity estimation [4].

In the following, we investigate the effects that a moving target shows in mmW SAR imagery. For this, we simulate multiple target environments with high and low resolution mmW SAR as provided by the Forschungsgesellschaft für Angewandte Naturwissenschaften e. V. (FGAN) MEMPHIS radar at K_a -band [5] and compare them to a large wavelength SAR such as the German Aerospace Center and Space Agency (DLR) E-SAR system at L-band [6].

We analyze radial target velocities that are in one case very slow with 1 m/s and in another one quite high, therefore causing multiple PRF ambiguities in the SAR. The effects of targets moving in cross-range are only implicitly covered. An extensive discussion of cross-range moving targets is given in [7].

The discussion of GMTI algorithms is not in the scope of this paper, but may be found in [8]-[13]. However, GMTI algorithms are based upon an understanding of displacement, defocus and smearing effects of moving targets. We show experimental data from a MEMPHIS data take where moving targets are imaged at high resolution.

2 Moving Target Effects

A mmW SAR system has some advantages as well as disadvantages when it comes to the imaging of moving targets. Because of the very short wavelength, we have a high sensitivity for even small velocities of targets. This relation is given by the fact that the Doppler shift f_d of a target moving with the radial velocity v_r may be expressed as

$$f_d = \frac{2v_r}{\lambda} \quad (1)$$

where λ is the wavelength. Unfortunately, v_r may easily become larger than the limit given by the system pulse repetition frequency (PRF), and f_d sensed by the SAR may be ambiguous with

$$v_r = \frac{(f_d + n \cdot \text{PRF})\lambda}{2} \quad \text{for all } n \in \mathbb{Z}. \quad (2)$$

This ambiguity may be resolved by using multi-channel SAR [8].

A direct effect of (1) is the displacement d of targets as given by

$$d = \frac{v_r}{v_s} \cdot R(t) \quad (3)$$

where v_s is the cross-range SAR platform speed and $R(t)$ the range to the target which is changing over time t . Obviously $R(t)$ shows a much different characteristics for moving targets than for static targets as described in [1]. The

advantage of a mmW SAR is its antenna aperture in cross-range that is generally very small. This implies that t is short for any given target and range smearing over multiple range resolution cells, appearing if

$$v_r t \geq \rho_r, \quad (4)$$

where ρ_r is the range resolution, is smaller than at larger antenna apertures. However, ρ_r may be in the order of centimeters for a high resolution mmW SAR and reduces the advantage of a short time t .

Another effect is a defocus of moving targets, depending on cross-range target velocity v_c and range acceleration a_r . As stated in [1], defocus happens if we have

$$\frac{2\pi}{\lambda R(t)} \left| \left(1 - \frac{v_c}{v_s}\right)^2 - \frac{a_r R_0}{v_s} - 1 \right| (v_s t)^2 \geq \pi \quad (5)$$

where R_0 is the range of closest approach to the target. Because λ is small in a mmW SAR, (5) is often true.

One might argue that, for a target T moving at a constant velocity in range with v_T , we have $v_r = v_T$ and $v_a = 0$, $a_r = 0$. However, this is only true at R_0 . At all other points in the aperture, we get

$$v_r = v_T \cdot \cos \varphi \quad (6)$$

with $\varphi \in [-\phi_d, \phi_d]$, where ϕ_d is the antenna aperture divergence angle, and

$$v_c = v_T \cdot \sin \varphi. \quad (7)$$

Additionally, because φ changes with time t , we have

$$a_r = \frac{d}{dt} v_r(t) = \frac{d}{dt} \cdot \cos \varphi(t). \quad (8)$$

Figure 1 illustrates these facts. Hence, even though we have $\phi_d \ll 1$ for mmW SAR, as opposed to large antenna apertures as in L- and P-band SAR, we still have a very sensitive system with high resolution, and even though a target may only be moving in range at a high speed, we might encounter range accelerations and cross-range velocities that are not negligible.

3 Simulated Data

3.1 Smearing and Displacement

To support the findings from Section 2, we simulated three high resolution target environments as shown in **Figure 2**. The first one in a) shows five static targets in a square of 20 m edge length. In the second one in b), the center target is not static but moves at a small velocity of $v_T = 1.0$ m/s in positive range direction.

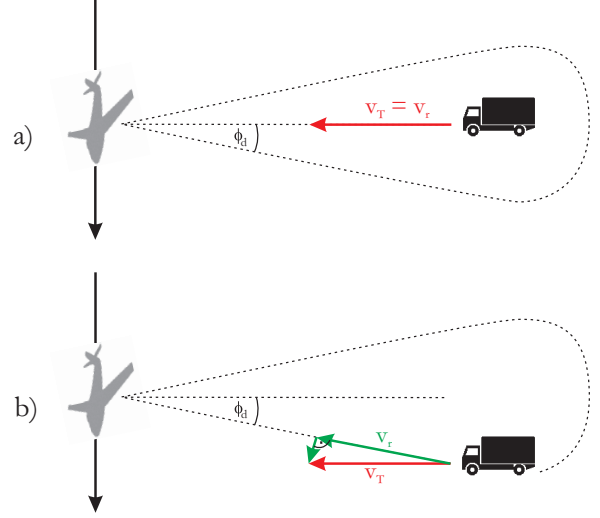


Figure 1: Geometry in SAR with a target moving in range. a) At beam center, the target velocity is only radial. b) Out of beam center, the target velocity has a radial as well as an along-track component.

In the third one in c), we used a high velocity $v_T = 26.71$ m/s in range for the center target. This is equal to 1.0 m/s with a Doppler shift ambiguity of 4 according to (2) since, for the three scenes, we used SAR system parameters corresponding to MEMPHIS with $\lambda = 8.571$ mm, a PRF of 1500 Hz, and a chirp signal bandwidth of 800 MHz resulting in $\rho_r = 18.75$ cm. The platform velocity is $v_s = 75.0$ m/s and the target range is $R_0 = 750$ m. While the slow target with 1 m/s is mainly displaced, the one with a much higher velocity is heavily smeared and defocused.

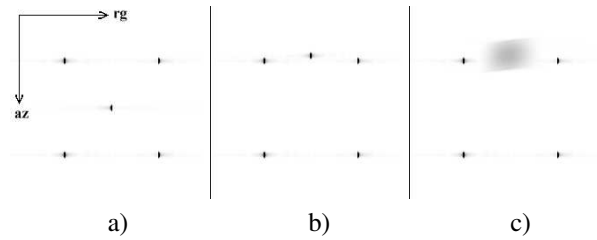


Figure 2: Moving target analysis at 35 GHz and a resolution of 0.19 m. a) 5 static targets forming a square with edge length 20 m. b) The center target is moving to the right (in range) with 1.0 m/s and gets displaced in azimuth. c) The center target is moving to the right with 26.71 m/s causing displacement, defocus and smearing.

The spectra $|S_a(\omega)|$ in the cross-range frequency domain for the static and the two moving center targets are shown in **Figure 3**. The slow target shows mainly a shift of the spectrum and a lower amplitude compared to the static target. The spectrum for the fast target, however, is clearly jolted. We have a loss of information in the spectrum and thus smearing and defocus in the time domain.

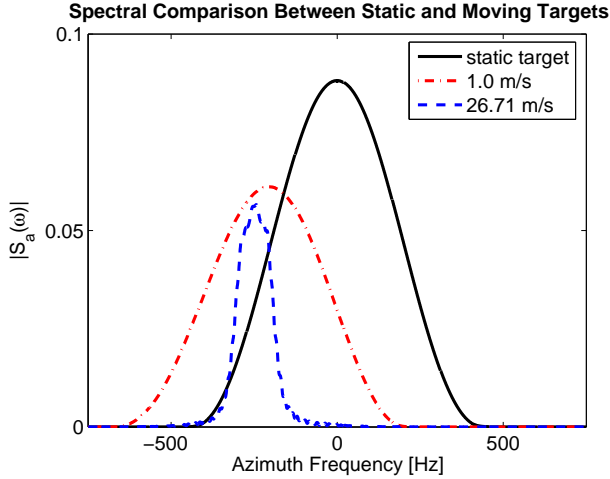


Figure 3: Spectra of the center targets from Figure 2.

3.2 Comparison to Other SAR Modes

While we used a high resolution simulation in Figure 2 with a chirp signal bandwidth of 800 MHz, in **Figure 4**, the chirp signal bandwidth is only 200 MHz. All other system parameters are the same. We see how the moving targets are defocused the same as in Figure 2, but because of a lower resolution, the effects appear less severe.

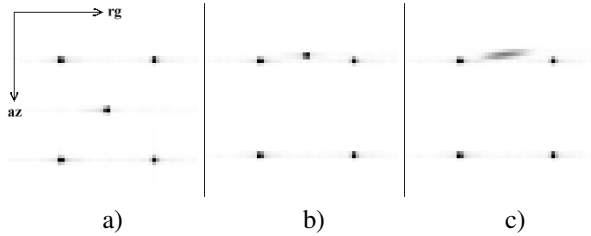


Figure 4: Moving target analysis at 35 GHz and a resolution of 0.75 m. a) 5 static targets forming a square with edge length 20 m. b) The center target is moving to the right (in range) with 1.0 m/s and gets displaced in azimuth. c) The center target is moving to the right with 26.71 m/s causing displacement, defocus and smearing.

To compare our findings with the effects of target motion in a completely different SAR system, we simulated the same five point targets in a square of 20 m edge length as imaged with a system derived from E-SAR L-band specifications. We chose a wavelength of $\lambda = 23.08$ cm, a PRF of 670 Hz, and a chirp signal bandwidth of 100 MHz resulting in $\rho_r = 1.5$ m. **Figure 5** shows the results. In a) the center target is again static. In b) the center target is moving in range with 1.0 m/s. It is displaced farther than in Figures 2 and 4 because of a faster platform velocity of $v_s = 100$ m/s and a greater range distance $R_0 = 4500$ m. In c) the center target is moving with 77.30 m/s, being the same as 1 m/s at the first Doppler ambiguity of $n = 1$ (see

(2)). It is smeared and defocused over the whole image, giving the scene a gray background. In a real data scene, the target would be lost in the clutter. One of the reasons for this strong smearing and defocusing effects is of course the large antenna aperture of 18° . Simulations with mmW parameters and an equally high target velocity of 77.30 m/s showed that there, too, the target will probably be lost in the clutter background.

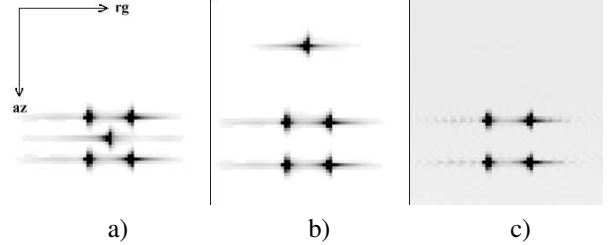


Figure 5: Moving target analysis at L-band (1.3 GHz) and a resolution of 1.5 m. a) 5 static targets forming a square with edge length 20 m. b) The center target is moving to the right (in range) with 1.0 m/s and displaced in azimuth. c) The center target is moving to the right with 77.30 m/s and its signal gets distributed over the whole image.

4 Experimental Data

In **Figure 6**, a SAR scene imaged with MEMPHIS at 35 GHz ($\lambda = 8.571$ mm), a PRF of 1618 Hz, and a chirp bandwidth of 800 MHz. Two Puch multi-purpose vehicles are visible, moving on a road in range and away from the sensor at 15 m/s. The movement causes a displacement away from the road as well as smearing effects. While the targets have real dimensions of $4.6 \text{ m} \times 1.7 \text{ m}$, the smeared and defocused SAR image thereof shows dimensions of around $17 \text{ m} \times 7 \text{ m}$.

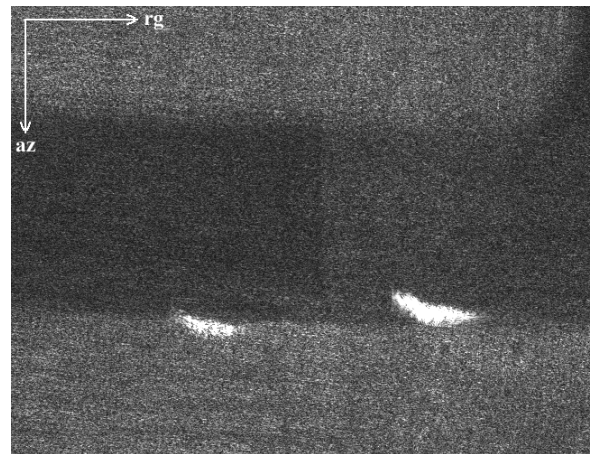


Figure 6: 35 GHz SAR image of two Puch multi-purpose vehicles moving on a road at 15 m/s in positive range direction. Image resolution is 0.19 m.

5 Conclusion

SAR systems working in the mmW domain have some clear advantages as well as disadvantages over other, more conventional systems when GMTI algorithms are applied. The small antenna aperture reduces smearing and defocusing effects of moving targets while at the same time, the small wavelength is very sensitive to minor movements. Unfortunately, the same small wavelength causes high Doppler frequency shifts requiring either a very large system PRF or additional target information to solve velocity measurement ambiguities.

We showed for simulated as well as real data how much targets are smeared and defocused at small and large target velocities in high resolution mmW SAR, and we compared simulated results to low resolution images and also to those of an L-band SAR. Overall, mmW high resolution SAR seems well suited for low speed GMTI and less so for fast moving targets. Still, because of the small antenna aperture, it is a SAR solution for GMTI that offers good detection probabilities.

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