Detection, Velocity Estimation and Imaging of Moving Targets with Single–Channel SAR

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Abstract

A method for detection of ground moving targets, for estimation of their velocities, and for compensation of their motion is presented. It is based on the evaluation of a sequence of single–look SAR images which is generated from conventional single–channel SAR data. The azimuth velocity component is obtained by estimating the displacement vectors of a moving target in consecutive images of the sequence. The range velocity component is estimated by evaluating the variation of the signal amplitude during the sequence. For moving target imaging (MTI), shift and blurring of the targets are compensated in the images. The moving targets are visualized either in a multilook image or in the sequence of single–look images.

1 Introduction

In synthetic aperture radar (SAR) images, ground moving targets appear defocused or at wrong positions depending on the direction of the target motion. A target moving in along–track (azimuth) direction causes a blurring in azimuth direction whereas a target moving in cross–track (range) direction causes mainly a displacement in azimuth direction. These imaging errors can be compensated for by detecting the moving targets, estimating their velocities and compensating their motion.

In general, either single– or multi–channel SAR systems can be used for moving target detection and moving target imaging (MTI). Single–channel SAR systems, i. e. systems with one receiving antenna, have the advantage of lower development and hardware effort and of less computational load for data processing. On the other hand, multi–channel SAR systems, i. e. along–track interferometric systems or those with phased array antennas, provide a better accuracy, especially in estimating the azimuth position of moving targets. This paper will focus on single–channel systems.

Concerning MTI with single–channel SAR systems, a number of algorithms have been proposed. Freeman and Currie proposed a MTI by filtering the Doppler spectrum. Choosing the pulse repetition frequency (PRF) to four times the clutter bandwidth, three bands with moving targets with different mean range velocity components are obtained [1]. Barbarossa and Farina estimate the target velocity indirectly by estimating the parameters of the chirp signal of a moving target in a time–frequency domain [2]. Another way is to calculate a Doppler rate map from the range compressed data and to estimate the azimuth velocity component from the Doppler rate and the range velocity component from the range migration as shown by Moreira and Keydel [3].

Here, a method for detection of moving targets, for estimation of their velocities and for compensation of the imaging errors is presented. Compared with the algorithms [1][2], the proposed algorithm has the advantage that also targets moving mainly in azimuth direction can be detected and that the PRF needs to be only about twice the clutter bandwidth. The compensation capability is an advantage when compared to [3]. Compared to an early version of this algorithm [4], an extension for the estimation and compensation of the range velocity component of moving targets has been made.

The proposed algorithm consists of five main steps as shown in Fig. 1. The first step is the generation of a

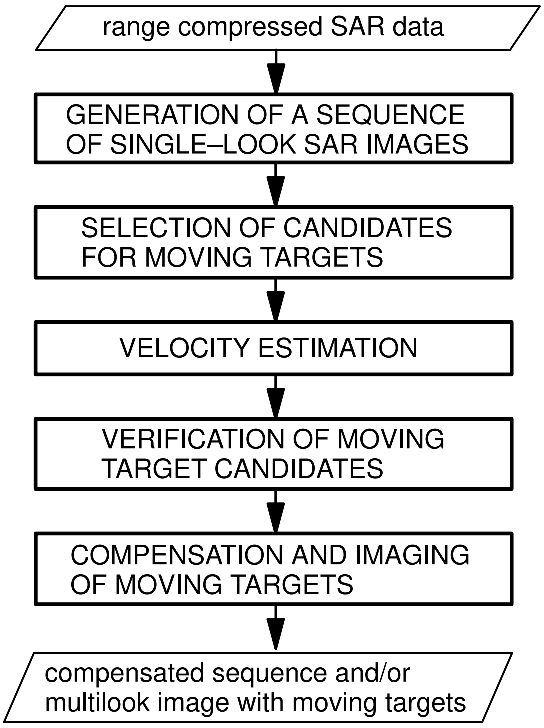


Fig. 1 Block diagram of the proposed algorithm

sequence of single–look SAR images. Afterwards, the selection of candidates, the velocity estimation and the verification of the estimates follow. The last step is the compensation of the target motion. An imaging of the moving targets overlaid on the clutter background is then possible in multilook images or in the sequence of single–look images. The latter possibility allows to visualize the target motion, whereas the multilook image provides the best quality with regard to low speckle noise.

2 Detection and Velocity Estimation of Moving Targets

This chapter describes the first four blocks in Fig. 1. The first block is the generation of the sequence of single–look SAR images, which is evaluated in the following blocks.

2.1 Generation of a Sequence of Single–Look SAR Images

The sequence of SAR images is generated from single–channel SAR raw data by processing images using data from various frequency bands out of the complete Doppler spectrum. Each image i shows the ground at a specific (azimuth) look angle

$$\theta_i = -\arcsin \frac{f_{l_i}\,\lambda}{2\,v_{Ax}}, \tag{1}$$

defined by the look center frequency f_{l_i}. The images are therefore called single–look images. In Eq. (1), λ and v_{Ax} denote the carrier wavelength and the antenna speed in azimuth direction x, respectively. For static targets the different look angles θ_i correspond with different times

$$t_i \approx t_0 + \frac{\theta_i\,R_{T_0}}{v_{Ax}} \approx t_0 - \frac{f_{l_i}\,\lambda\,R_{T_0}}{2\,v_{Ax}^2} \quad \text{for } \sin\theta_i \ll 1, \tag{2}$$

where R_{T_0} is the distance between antenna and target and t_0 is an initial time.

In order to get a geometrically correct and static background in the images of the sequence, a ground range projection and a range migration correction is performed. In this manner we get a sequence of consecutive images where the motion of the moving targets can be observed.

2.2 Selection of Candidates for Moving Targets

The velocity estimation described in the next section will be done for each moving target individually. As no moving targets have been detected so far, candidates for moving targets are selected first. This is done by searching for small regions with a locally high signal amplitude. The signal amplitude in a SAR image is a measure for the radar cross section (RCS). Due to the metallic surface of moving targets their RCS is assumed to be higher than the surrounding. By reason of plausibility, the maximum allowed number of pixels of a candidate is limited which reduces the number of candidates. The selection of candidates simultaneously leads to their shape.

2.3 Velocity Estimation

The velocity estimation algorithm is divided into two parts, one for each velocity component.

2.3.1 Estimation of the Azimuth Velocity Component

The azimuth velocity component of a moving target candidate is obtained by estimating its displacement vector. The displacement vector is estimated using a block matching algorithm [5] which searches for the best match between blocks in two successive images. In the second of a pair of images the block is set centered around a candidate. Then in the previous image that position is searched which leads to the maximum correlation between the two blocks. The difference of the positions is taken as displacement vector. It is measured in the unit pixel per image.

In [4], it is shown that the azimuth component of the target velocity can be estimated from the azimuth component of the displacement vector Δx as

$$\hat{v}_{Tx} = v_{Ax} \cdot \left[1 - \left(1 - \frac{2\,\Delta x\;\delta x\;v_{Ax}}{\Delta f_l\;\lambda\;R_{T_0}} \right)^{-\frac{1}{2}} \right], \tag{3}$$

where δx is the pixel spacing in azimuth direction and Δf_l is the difference between the look center frequencies of two successive images. Eq. (3) is an enhanced version of

$$\hat{v}_{Tx} \approx \frac{\Delta x\;\delta x}{2\Delta t} = -\frac{\Delta x\;\delta x\;v_{Ax}^2}{\Delta f_l\;\lambda\;R_{T_0}}, \tag{4}$$

where $\Delta t = t_i - t_{i-1}$, which is only valid for small target velocities $|v_{Tx}| \ll v_{Ax}$. The left side of Eq. (4) has been shown by Ouchi [6], where the right side is added here to show the relation to Eq. (3).

2.3.2 Estimation of the Range Velocity Component

The displacement vector component in range direction Δy is not an accurate measure for the range velocity component v_{Ty}, since for radially moving targets the change of the positions in the images in range direction is erroneous due to the range migration correction. Thus estimating the range velocity component will be done in another way.

Assuming a target with a range velocity component v_{Ty}, the signature of this target in the Doppler spectrum is shifted by

$$f_{D_T} = -\frac{2\,v_{T_y}\sin\gamma}{\lambda}, \tag{5}$$

where γ denotes the incidence angle. This Doppler shift causes a shifted appearance of the target in the sequence of SAR images by

$$\Delta t_T \approx -\frac{f_{D_T}\,\lambda\,R_{T_0}}{2\,v_{Ax}^2} = \frac{v_{Ty}\,\sin\gamma\,R_{T_0}}{v_{Ax}^2}. \tag{6}$$

With the terms reversed the range velocity can be estimated by estimating this temporal shift. Here, this temporal shift is estimated by evaluating the signal amplitude of a target from image to image. The signal amplitude is a product of the RCS and the antenna pattern. By weighting the signal amplitude in each image with the time t_i of this image one gets the temporal center of gravity $\hat{\Delta t}_T$. Application of Eq. (6) leads to an estimate for the range velocity component.

2.4 Verification of Moving Target Candidates

The candidates are tracked from image to image according to their estimated displacement vectors. If the estimated velocities are non–zero and remain nearly constant during a fixed number of images, the candidate will be verified to be a moving target. Thus, static candidates are sorted out.

In order to get a reliable azimuth velocity, the velocity estimates according to Eq. (3) from successive image pairs are averaged.

3 Compensation and Imaging of Moving Targets

The compensation of the imaging errors is done by shifting each moving target to the reference position in each image of the sequence, using the previously estimated shape. The reference position is attained when the target is in the center of the antenna beam. It is calculated by considering the azimuth positions and the estimated range velocity component. The latter one requires a correction of the azimuth position by

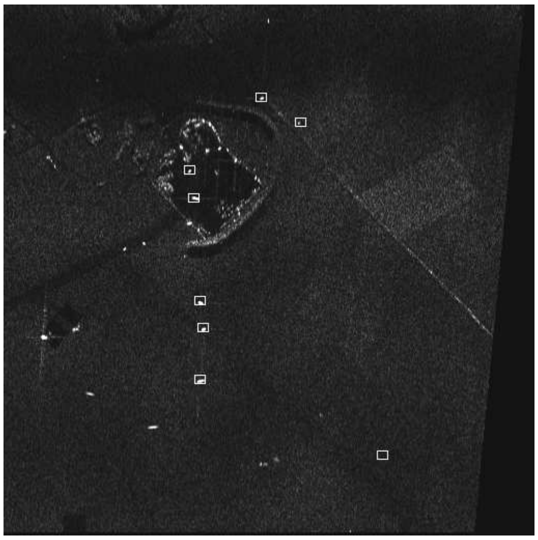
$$\Delta x = \frac{\hat{v}_{Ty}\,\sin\gamma}{v_{Ax}} \cdot R_{T_0}. \tag{7}$$

By averaging the middle images of the sequence centered around that image with a look center frequency similar to the mean Doppler frequency one gets a compensated multilook image where the moving targets appear focused at the reference position. The second imaging possibility is to perform only the azimuth shift according to Eq. (7) in the single–look images. This yields a sequence where the motions of the targets remain visible but the targets appear nearly at the right positions.

4 Results

The proposed algorithm has been applied to simulated and to real raw data. Figures 2 and 3 show sample images out of the sequence for simulated and for real raw data respectively. The simulated data are obtained by simulating raw data of 15 moving targets with different velocities and superimposing them on real clutter data. The azimuth positions originally lie on a vertical line in the middle of Fig. 2 but are shifted due to the different range velocity components. The scene in Fig. 3 with one car and two trucks moving from the lower left to the upper right demonstrates the successful detection and velocity estimation of moving targets with real data.

In Fig. 4, a multilook image, the common output of a SAR processor, is shown using the same data as in Fig. 2. The moving targets appear blurred and shifted.



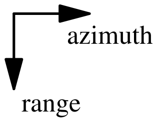


Fig. 2 Single–look image generated from simulated raw data of 15 moving targets superimposed on real clutter data;
8 of the moving targets are detected at this moment as marked by white squares

Fig. 3 Single–look image generated from real raw data containing two trucks and one car in the left part of the image; Both trucks have been detected as marked by white squares;
The targets are not compensated yet.

After the compensation of the imaging errors and the averaging of the single–look images a compensated multilook image as shown in Fig. 5 is obtained. The displacement and blurring of all targets except one is compensated. The moving targets are displayed near their real positions.

By applying the algorithm to simulated data, the mean standard deviation of the error of the azimuth velocity estimates is 5 km/h (1.4 m/s) for an azimuth velocity component of up to 100 km/h and a range velocity component of up to 50 km/h. The standard deviation of the error of the range velocity estimates is 17 km/h for range velocities of up to 75 km/h. This value is not very accurate due to the fact that a moving target is not selected as candidate in every image. However, the accuracy is higher for targets which are detected in a greater number of images of the sequence (e. g. 10 of 30 images) or when the velocity is less than about 40 km/h.

5 Conclusions

In this paper, a method for detection of moving targets and for estimation and compensation of their velocities has been presented. The method evaluates the temporal correlation in a sequence of single–look SAR images. These images show the ground at different look angles and therefore at different times. By tracking the targets from image to image and by evaluating the change in position and the signal amplitude, the target velocities are estimated with a mean standard deviation of the error of 5 km/h / 17 km/h for the azimuth / range component, respectively. It has been shown that either a compensated multilook image or a compensated sequence can be generated where the moving targets appear focused and at the estimated positions.

The advantages of the method are the toleration of a small PRF and the capability of detecting also targets having a range velocity component of zero. Further work will focus on improving the estimation of the range velocity component.

6 Acknowledgments

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7 Literature

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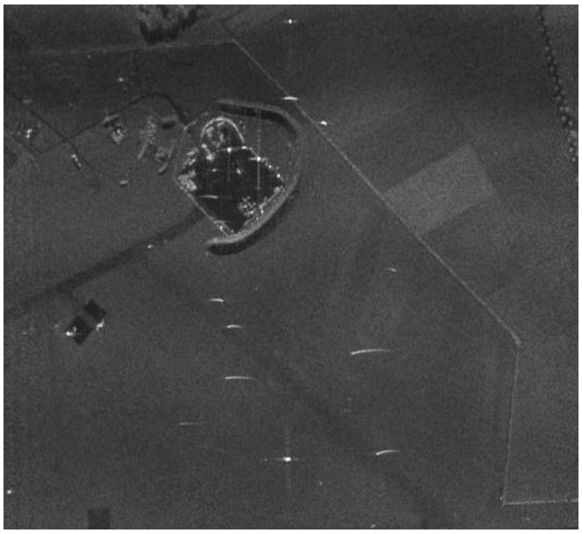

Fig. 4 Multilook image generated from the same data as in Fig. 2; the moving targets appear blurred and shifted

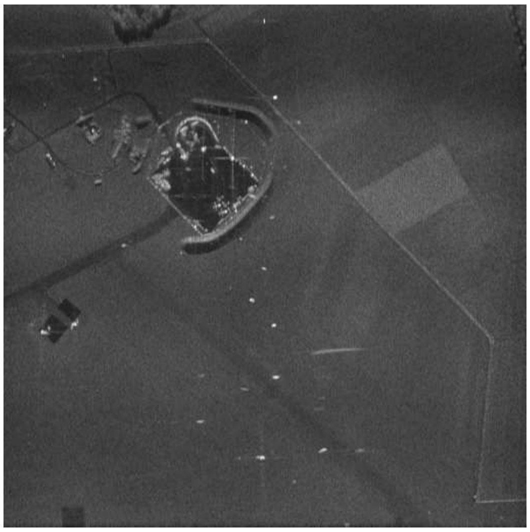

Fig. 5 Compensated multilook image; all moving targets except one have been detected and compensated and appear focused at the estimated reference positions