Detection and Velocity Estimation of Moving Objects in a Sequence of Single–Look SAR Images

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Abstract — A method for detection of point–like moving objects and for estimation of their velocities with airborne synthetic aperture radar (SAR) is presented. This method is based on evaluation of the temporal correlation in a sequence of single–look SAR images which are processed using look filters with different center frequencies. In these images, candidates for moving objects are detected and a displacement vector estimation is performed for each candidate using a block matching algorithm as known from e. g. videotelephony. From the displacement vectors the velocities of the candidates in azimuth direction are calculated. The proposed algorithm has been applied to simulated and real raw data. The azimuth velocity component has been estimated with high accuracy, and a high detection probability with a low false alarm rate is reached.

INTRODUCTION

Synthetic aperture radar (SAR) is a powerful tool to produce high resolution microwave images of the ground. Since for SAR processing it is assumed, that the observed objects are static, moving objects cause errors in the SAR images. There are two significant kind of errors, depending on the direction of the motion. An object which moves in azimuth direction is defocused in azimuth direction whereas an object which moves in range direction is shifted in azimuth direction in the SAR image [1]. To compensate for these errors it is necessary to detect the moving objects and to estimate their velocities.

Most of the previously proposed algorithms for motion estimation of point–like moving objects are not able to detect objects which only have an azimuth velocity component. They usually work on range compressed SAR raw data, either transformed to the Doppler frequency domain (e. g. [2], [3]), or to a time–frequency domain [4]. A restriction is that the pulse repetition frequency (PRF) normally has to be much higher than the Doppler bandwidth of the clutter.

In this paper, a new method for detection of arbitrarily moving ground–based objects and for estimation of the azimuth velocity component is presented, which also works with a small PRF. This method is based on evaluation of the temporal correlation in a sequence of single–look SAR images. These images are processed from different overlapping frequency bands with constant look bandwidth out of the Doppler spectrum. The images show the ground at different look angles and therefore at different times. Thus, the objects appear at different positions in the several images and the velocities of the objects can be estimated.

The following paragraphs of the paper describe the generation of the sequence of single–look SAR images and the three main steps of the detection and velocity estimation algorithm. Afterwards main results concerning the detection probability and the estimation accuracy are given.

GENERATION OF THE SEQUENCE OF SAR IMAGES

The proposed method is based on estimation of the displacements of point–like moving objects in a sequence of single–look SAR images. The generation of this sequence is carried out as follows. First the Doppler spectrum of the range compressed SAR raw data is calculated by performing a fast Fourier transform (FFT) in azimuth direction. Then the Doppler spectrum is subdivided into several overlapping bands and a single–look image is processed from each band. The images show the ground at different (horizontal) look angles θ_i, which depend on the look center frequencies f_{li}, as given by

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

where v_{Ax} is the platform velocity, which moves in positive azimuth direction, denoted by x, and λ is the carrier wavelength. The different look angles also imply that the images show the ground at different times. The look bandwidth has to be chosen carefully. If it is too small, the azimuth resolution will decrease, on the contrary if it is too large, the quickly moving objects will be defocused and will lose the point–like property.

The images of the sequence are ground range corrected and then a range migration correction is performed by shifting the images in range direction according to the change of the distance between antenna and ground at different look angles. After this manipulation the stationary background in the images remains at the same position, whereas the positions of the moving objects change from image to image. Due to the single look processing the images contain a lot of speckle noise. This might be interpreted as a moving object in some cases. To avoid this, a three step algorithm is performed, which evaluates the images of the sequence consecutively, beginning at the image with the highest look center frequency. The first step is the detection of candidates for moving objects, which later are verified.

DETECTION OF CANDIDATES FOR MOVING OBJECTS

In each image of the generated sequence point–like objects are selected as candidates for moving objects. The search is

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performed by starting at the pixel with the highest intensity, which depends on the radar cross section. Then this pixel and the surrounding pixels are selected as one candidate if the following criteria are fulfilled:

- the brightest pixel of a candidate has a higher intensity than a threshold adapted to the mean global intensity of the image,
- the number of pixels belonging to one candidate is between a lower and an upper bound; the upper bound depends on the length of the objects in azimuth direction and is therefore be chosen according to the maximal detectable velocity;
- the mean intensity of the pixels of a candidate is noticeably higher than the mean intensity of the surrounding area,
- the candidate covers a closed area, and
- no pixel of one candidate adjoins a pixel of another candidate.

After the positive or negative finishing of this task, the previous steps are repeated for the remaining pixels with the same intensity and afterwards for those with less intensity until a threshold is reached.

VELOCITY ESTIMATION

After having detected candidates for moving objects, for each candidate a displacement vector is estimated using a block matching algorithm as known from e. g. videotelephony [5]. This algorithm estimates the displacement of parts of the image between two successive images s_1 and s_2 of the sequence, which are called frames in this chapter. To obtain the displacement vector, a window is positioned in the frame s_2, so that the candidate lies in the center of it. Then in frame s_1 another window is put at the same position. The aim is, to find the best match between the two windows by shifting the window in frame s_1 on every position within a neighborhood (full search method). For that, one of the following four matching criteria are used, the cross correlation coefficient (CCC), the normalized cross correlation function (NCCF), the mean square error (MSE), and the mean absolute difference (MAD). The NCCF criterion shows the best results. The results of the MSE criterion are nearly as good as the results of the NCCF, with the advantage of a faster implementation. The NCCF is defined by

$$C_{Ns_2s_1}(\Delta x, \Delta y) = \frac{\sum_{x,y} [s_2(x,y) \cdot s_1(x - \Delta x, y - \Delta y)]}{\sqrt{\sum_{x,y} s_2^2(x,y) \cdot \sum_{x,y} s_1^2(x - \Delta x, y - \Delta y)}} , \qquad (2)$$

where (x, y) is one of the positions inside the window, and Δx and Δy are the position shifts between the two windows. Equation (2) has to be evaluated for each different position of the window in the first frame. The motion vector in pixel / frame for the selected candidate is then given by that shifts Δx and Δy which maximize the $C_{Ns_2s_1}$.

The azimuth velocity component is calculated from the displacement vector component $v_{Tx_{pix}} = \Delta x$ in azimuth direction and the range dependent time difference between two successive frames which is given by

$$\Delta t \approx \frac{\Delta\theta \ R_0}{v_{Ax}} \approx -\frac{\Delta f_l \ \lambda \ R_0}{2 v_{Ax}^2} \quad \text{for } \sin\theta \ll 1, \qquad (3)$$

where $\Delta\theta$ is the difference between the look angles of adjacent frames, R_0 is the minimal distance between antenna and object candidate, and Δf_l is the difference between the look center frequencies.

Let δx be the pixel spacing in azimuth direction, then we can calculate the observed velocity in azimuth direction to

$$v_{Tx_{obs}} = \frac{v_{Tx_{pix}} \ \delta x}{\Delta t} . \qquad (4)$$

This velocity is not the real one, because the objects do not appear at the right positions in the different images. Ouchi [6] showed that the azimuth velocity component has to be divided by a factor of 2 to get the real velocity. So the estimated velocity $v_{Tx_{est}}$ finally becomes

$$v_{Tx_{est}} \approx \frac{v_{Tx_{pix}} \ \delta x}{2 \ \Delta t} = -\frac{v_{Tx_{pix}} \ \delta x \ v_{Ax}^2}{\Delta f_l \ \lambda \ R_0} . \qquad (5)$$

Here beside some other approximations, the assumption is made that $v_{Tx}/v_{Ax} \ll 1$.

Additionally, it deserves mentioning that the range velocity component cannot be well estimated that way, because the range migration correction causes a warping of the range position of those objects, whose range velocity component is not zero. However, this warping can be avoided if the Doppler shift due to motion in range direction is compensated prior to the generation of the sequence.

VERIFICATION OF MOVING OBJECTS

The candidates are verified to be moving objects if their displacement vectors remain quite constant during a fixed number of images. This means that the absolute value and the angle of motion may only change within a fixed range. If this is fulfilled, the counter for this candidate will be incremented and it will be finally detected as moving object, if the dedicated number of images is reached.

Finally, in order to improve the reliability of the estimated azimuth velocity component an averaging over all previously counted, estimated values is carried out.

RESULTS

The proposed method has been applied to simulated raw data and to real raw data. A PRF of 1.5 times the clutter bandwidth and a sequence with 16 images are used. The proposed algorithm estimates the azimuth velocity component with high accuracy, i. e. the average of the relative error is 8.0 % for positive v_{Tx}, and 18.9 % for negative v_{Tx} ranging from ± 10 km/h (± 2.8 m/s) to ± 50 km/h (± 13.9 m/s), respectively. The attained accuracy depends on the moving direction of the object due to the approximations in (5). For this results the

NCCF criterion and simulated raw data of moving objects superimposed by real clutter data with a signal–to–clutter ratio of 0 dB are used. The platform velocity is 300 km/h or 83 m/s. All moving objects with a minimum azimuth velocity component of 10 km/h are detected even if they move in direct neighborhood to a strong stationary scatterer. At smaller velocities the detection probability decreases slightly. The false alarm rate is about 2 %. The maximal detectable velocity can be adjusted; it depends on the maximal Δx in (2) and the maximal number of pixels for the detection of candidates.

The proposed method also works well if the objects have an additional range velocity component v_{Ty}. In an example two images out of a sequence with 16 images are shown. The azimuth direction x runs horizontal. The 5 moving objects in the scene have the velocity components v_{Tx}=30 km/h and v_{Ty} ranging from –20 to +20 km/h. Fig. 1 shows image No. 6 of the sequence, where 2 objects out of 5 are already detected, which is marked with a white square. In Fig. 2 image No. 11 of the sequence is shown, where all moving objects are detected.

First results by applying the method to real SAR raw data show that the detection probability slightly decreases, but that the algorithm still works well.

CONCLUSIONS

In this paper a new method for detection and estimation of the azimuth velocity component of moving objects has been presented, which works on a sequence of single–look SAR images. These images show the ground at different look angles and therefore at different times. So the object velocities can be estimated by evaluating the temporal correlation of successive images. The advantages of the method are, that it works with a small PRF and that also objects can be detected, whose range velocity component is zero. A high estimation accuracy is reached, even if the objects are superimposed by real clutter data. The method only works well for the azimuth velocity component, but it could be extended in order to estimate both components of the velocity if the Doppler shift due to motion in range direction is compensated prior to the generation of the sequence.

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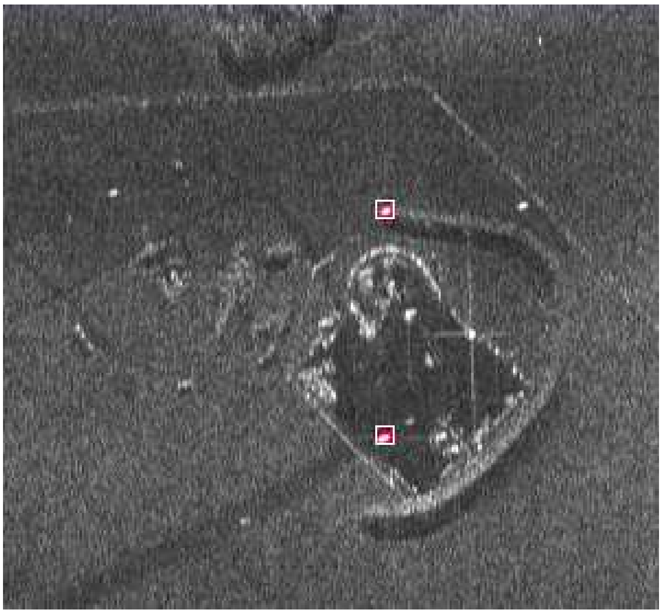

Fig. 1 Single–look image No. 6 from the generated sequence, look center frequency is 125 Hz; 2 out of 5 moving objects are detected (marked with a white / red square)

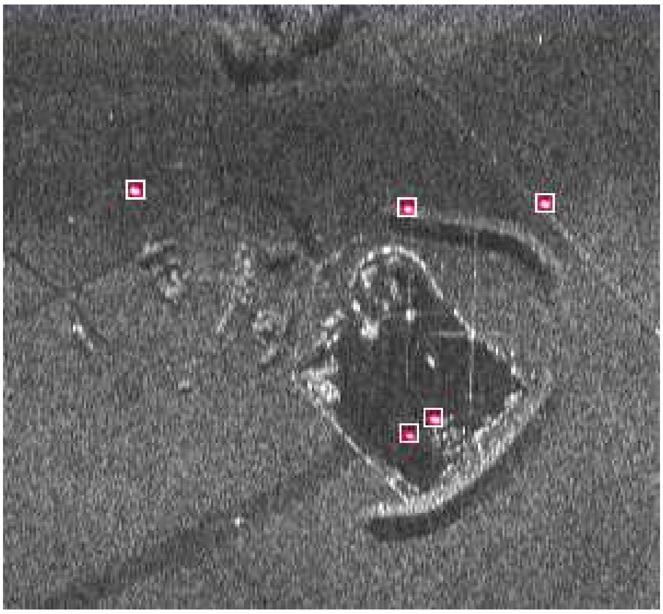

Fig. 2 Single–look image No. 11 from the generated sequence, look center frequency is –125 Hz; all moving objects are detected