INTEGRATING SPACE-TIME PROCESSING INTO TIME-DOMAIN BACKPROJECTION PROCESS FOR DETECTION AND IMAGING MOVING OBJECTS

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ABSTRACT

This paper discusses a possibility to integrate space-time processing into the time-domain backprojection process. This combination allows detection as well as imaging moving objects. Two space-time techniques, Displaced Phase Center Antenna (DPCA) and Space-Time Adaptive Processing (STAP), are considered for this integration. Simulated results based on the LORA parameters demonstrate the efficiency of detection and imaging moving objects.

Index Terms— space-time adaptive processing, backprojection, detection, moving object, LORA

1. INTRODUCTION

Detection and imaging moving objects, even hidden by strong clutter on the ground, make Synthetic Aperture Radar (SAR) more and more important for Ground Moving Target Indication (GMTI). Moving target detection is most commonly performed by GMTI radars based on antenna array solutions without imaging capability while SAR systems do not facilitate indicating the presence of moving objects in an imaged SAR scene. Moving targets are usually displaced and defocused in a SAR image. Distinguishing them from strong ground clutter requires much effort.

The possibility to use SAR for moving target detection has been discussed in several publications, which can be divided into two categories: detection techniques for single-channel and multi-channel SAR. For single-channel SAR, the most primitive detection technique has been based on Doppler shift originated by moving objects. However, such techniques only work under certain circumstances. For example the speed of the moving objects needs to be high enough to produce Doppler shift, which are distinguishable from the surrounding stationary clutter. Another simple detection technique is relied on shadow phenomenon caused by the displacement if moving objects are present at an image scene. The detection is possible in strong ground clutter SAR environment. One of the more advanced detection techniques, named moving target detection by focusing, appears in some recent publications. The principle of the technique is to focus moving targets with correct Normalized Relative Speed (NRS) while defocus ground clutter, i.e. suppress ground clutter, simultaneously. The technique is shown to be suitable for ultra-wideband (UWB) SAR systems and can be combined with space-time processing techniques for more reliable detection.

Applying space-time processing techniques to multi-channel SAR for detection and imaging the moving objects is a topic of interest. Displaced phase center antenna (DPCA) [1], i.e. non-adaptive, and space time adaptive processing (STAP) [2] are known as mostly used space-time processing techniques. Using DPCA as a data pre-processing technique for moving target detection in dual-channel UWB SAR has been introduced in [3]. According to this proposal, dual-channel SAR data is first handled by DPCA to suppress ground clutter. The suppressed clutter data is then processed by the moving target detection by focusing technique. This combination is supposed to provide a reliable detection. In [4], STAP is also considered as a pre-process for SAR data to improve as much as possible the signal to clutter noise ratio (SCNR) for detection. Further processing such as filter and estimation can be applied to the SAR data to reconstruct the SAR image of the moving objects.

The goal of this paper is to present a possibility to integrate different space-time techniques into the time-domain local backprojection process for detection and imaging moving objects. Integrating STAP into the local backprojection process in wideband radar have once suggested in [5]. In this paper, two space-time processing techniques, i.e. DPCA and STAP, are subjects for this combination. The integration is expected to lighten the strict requirements as well as improve the practicality of two techniques. The proposal is demonstrated and evaluated by simulations based on the LORA parameters.

The paper is organized as follows. Section 2 reviews two space-time techniques, i.e. DPCA and STAP. Section 3 describes the local backprojection process. Integrating two space-time techniques into local backprojection processing is proposed in Section 4. Simulated results based on the LORA parameters are presented in Sections 5. Section 6 provides the conclusions.

*The authors would like to thank the KK-Foundation for making this research project possible, and the support from Swedish Defence Research Agency, Saab Bofors Dynamics, Saab Electronic Defence Systems and RUAG Space.

2. SPACE-TIME PROCESSING

The ability to detect moving targets in an illuminated SAR scene depends strongly on the ability to suppress ground clutter and noise, i.e. ability to filter the signal. The ground clutter is interpreted as the radar backscattering in the illuminated SAR scene while the noise is thermal noise originated from the environment and the SAR system.

The simplest space-time processing technique is known as DPCA [1]. Basically, the technique is based on a side looking array with two antennas aligned along the flight track and spaced by a Pulse Repetition Interval (RPI). Two successive pulses transmitted and received in turn by the forward and backward antennas. The motion of the aircraft after one PRI places the backward antenna to the previous position of the forward antenna. It is obvious that two successive pulses are transmitted and received at the same position in space but separated by one PRI in time. Simple ground clutter suppression is obtained by subtracting the second echo received by the backward antenna from the first echo received by the forward antenna. However, DPCA has very high demands on, for example, the straight flight track, constant platform speed and identical channels. From the detection's point of view, DPCA is quite sensitive to the speed of the moving targets. The subtraction in DPCA can suppress the ground clutter but can also raise the noise level significantly.

STAP refers to an efficient space-time processing technique providing improved detection of moving objects obscured by ground clutter and noise. Let's have a look again at the theory of adaptive radar developed in [2]. According to Theorem 1, the optimum weights, which maximize signal to noise ratio (SNR), are given by

$$\mathbf{w} = \kappa \mathbf{R}^{-1} \mathbf{s}^{*} \tag{1}$$

where the asterisk denotes complex conjugation operation, κ is a nonzero complex number and $\mathbf{R}$ is the noise covariance matrix. The echo from a target at a given range delay is denoted by $\mathbf{s}$ which can be represented by

$$\mathbf{s} = \left[s_{11} \cdots s_{1M} \cdots \; s_{N1} \cdots s_{NM}\right]^{\mathrm{T}} \tag{2}$$

where N is the number of antennas and M is the number of samples yielded by each antennas. The subscript T denotes transpose operator. The theory can be further extended for the case where an object is obscured by ground clutter and noise. In this case, the NM coefficients of the optimum filter, which maximize signal to clutter noise ratio (SCNR), is also represented by (1). However, $\mathbf{R}$ is now interpreted as the clutter plus noise covariance matrix

$$\mathbf{R} = \mathrm{E}\left\{(\mathbf{c}+\mathbf{n})(\mathbf{c}+\mathbf{n})^{\mathrm{H}}\right\} \tag{3}$$

where $\mathbf{c}$ and $\mathbf{n}$ denote clutter and noise vectors, respectively. The subscript H denotes complex conjugate transpose (Hermitian transpose) operation. The main disadvantage of STAP is the computational burden for $\mathbf{R}^{-1}$.

3. TIME-DOMAIN BACKPROJECTION

In SAR processing, backprojection refers to a linear transformation from the radar echo to a SAR image. The superposition of backprojected radar echo to reconstruct the illuminated scene (x_0, r_0) is represented by the integral

$$h(x_0, r_0) = \int_{-\frac{t_i}{2}}^{+\frac{t_i}{2}} g\left(v_{pl}t, \sqrt{(v_{pl}t - x_0)^2 - r_0^2}\right) dt \tag{4}$$

where t_i is the integration time, v_{pl} denotes the speed of the platform, t indicates azimuth-time (slow-time) and $g(x, r)$ represents the range-compressed radar echoes. To save the processing time, it is recommended to process the data on a subaperture and subimage basis, i.e. local processing. Based on this basis, the complete aperture and the full SAR image are segmented in L subapertures and K subimages, respectively. The selection of subaperture and subimage sizes depends strongly on SAR system parameters, required image quality and processing time. However, any selection must ensure the phase error to be smaller than $\pi/8$ (far field condition). The reconstruction of the imaged scene is therefore split into two stages, beam-forming and approximately backprojection.

In the beam-forming stage, from the center of the $l-$th subaperture x_l, the $k-$th beam aiming at the center of the $k-$th subimage is formed by a superposition of all radar echo data in the $l-$th subaperture. The $k-$th subimage is then approximately backprojected by the $k-$th beam. This procedure will be repeated for all subapertures. The full SAR image is retrieved by a coherent combination of all subimages.

4. INTEGRATING SPACE-TIME PROCESSING INTO BACKPROJECTION PROCESS

The integration of the space-time processing techniques, which are mentioned in the previous section, should satisfy several criteria as follows. The integration should lighten the strict demands of DPCA. DPCA might therefore not be considered as a data pre-process as suggested in [3] but a data process after motion compensations. The integration should also reduce the computational burden for $\mathbf{R}^{-1}$. For these reasons, we propose to integrate the space-time processing techniques into the beam-forming stage in the local backprojection process for detection and imaging moving objects. Fig. 1 sketches the block diagram of the proposal. According to the moving target detection and imaging scheme, the range-compressed SAR data collected by each antenna is processed separately in the beginning of the beam-forming stage. Each antenna creates K beam-matrices with the dimension of $P \times M$ where P is the number of aperture positions in one subaperture. The k-th beam is formed by summing P rows of the k-th beam-matrix together.

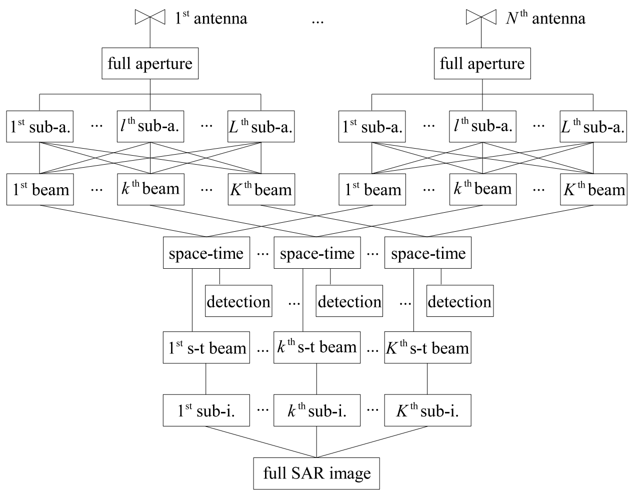

Fig. 1. Moving target detection and imaging scheme. In the scheme, the terms sub-a., sub-i., and s-t beam denote subaperture, subimage, and space-time beam respectively.

For DPCA implemented on dual-channel SAR data, the k-th beams of the forward-channel and backward-channel, which are at the same positions in space but separated by an integer number of PRI in time, are stacked in a column vector as

$$\mathbf{z} = [z_{11} \cdots z_{1M} \cdots \; z_{N1} \cdots z_{NM}]^{\mathrm{T}} \tag{5}$$

where $N = 2$. The m-th beam sample of the k-th space-time beam is estimated by

$$\mathbf{y}(m) = \mathbf{w}_m \mathbf{z} \tag{6}$$

where $\mathbf{w}_m$ is a row vector with the dimension of NM and defined by

$$\mathbf{w}_m(n) = \begin{cases} +1 & n = m \\ -1 & n = m + M \\ \;\;0 & \text{elsewhere} \end{cases} \tag{7}$$

Since DPCA is performed on the beams, the effects of the motion errors, which can lead to the poor performance of DPCA, are minimized.

For STAP, the m-th beam sample of the k-th space-time beam is also found from (5). However, the optimum weights $\mathbf{w}_m$ are estimated by (1). The dimension of the clutter plus noise covariance matrices in (1), i.e. $NM \times NM$ decided by the number of the considered antennas and size of subimages. For a small size of subimages, the computational cost for $\mathbf{R}^{-1}$ will be reduced significantly compared to the case where the dimension of the covariance matrices is decided by the number of antennas and the range samples yielded by each antenna. The number of STAP operations for the full SAR aperture is also reduced to a factor of P due to the combination of the aperture positions in one subaperture.

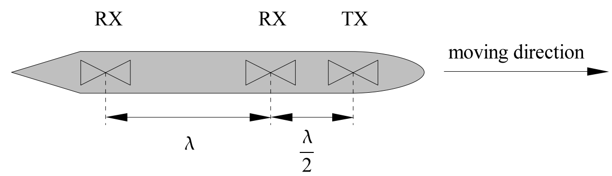

Fig. 2. LORA antenna array. λ denotes the wavelength.

For moving target detection, two hypotheses on $\mathbf{z}$ are given: a moving object exists (hypothesis $\mathbf{H_1}$) or no moving object exists (hypothesis $\mathbf{H_0}$) in the processed SAR scene (subimage). If Λ is a detection threshold, the Likelihood Ratio Test (LRT) for moving target detection is given by

$$\begin{matrix} \mathbf{H_1} : |\mathbf{y}(m)| \geq \Lambda \\ \mathbf{H_0} : |\mathbf{y}(m)| < \Lambda \end{matrix} \tag{8}$$

The space-time beams with clutter suppression can be used further for imaging the moving objects. For UWB SAR, focusing moving targets with NRS is performed in the subimage formation stage.

5. SIMULATION RESULTS AND EVALUATION

In this section, we demonstrate the proposed integration of the space-time processing techniques into the backprojection process. The reference system for simulations is LORA operating in the frequency range of $200 - 800$ MHz. For GMTI purposes, this system is configured as a bistatic SAR system with three antennas (one transmits and two receive simultaneously) and uses the frequency range of $307.2 - 332.8$ MHz. Fig. 2 plots this arrangement. With the given element spacing, the displacement of the phase center of the forward and backward antenna is approximately $\lambda/2$, i.e. five aperture positions with LORA parameters. In the simulation, the ground scene is simulated by one arbitrary moving object. The object is point-like scattering and its radar cross section (RCS) is normalized to $\sigma = 1$. The ground clutter is simulated by random stationary point targets spreading over all ground scene. The RCSs of these stationary targets vary in the range $0 < \sigma \leq 4$. The thermal noise is assumed to be AWGN with the noise level is -20 dB. Fig. 3.a plots an example of the beams which are formed only by the forward-channel SAR data. It is almost impossible to detect the moving target from the surrounding ground clutter and noise. Fig. 4.a shows the SAR image reconstructed from the forward-channel beams without space-time processing. No image of the moving target is achieved since it is totally hidden by the ground clutter.

In the first demonstration, we apply DPCA on dual-channel SAR data according to the following procedures. The forward-channel SAR data is delayed by five aperture positions to achieve the transmitted and received pulses at the same position in space but separated in time. The beams

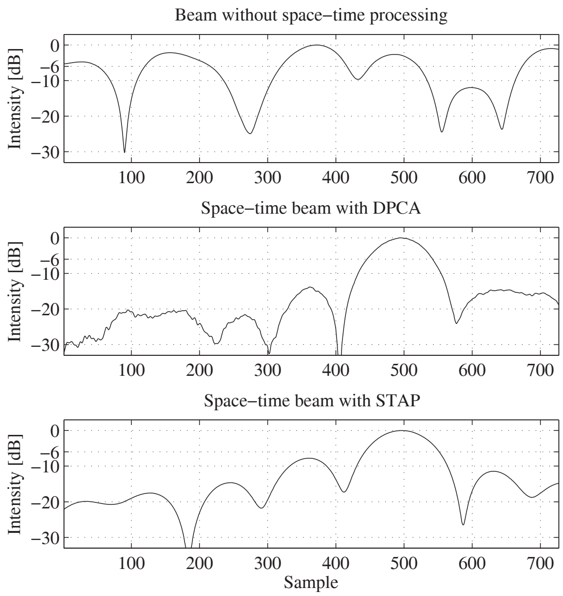

Fig. 3. The beams with and without space-time processing. (a) forward-channel beam, i.e. no space-time processing, (b) space-time beam with DPCA, (c) space-time beam with STAP.

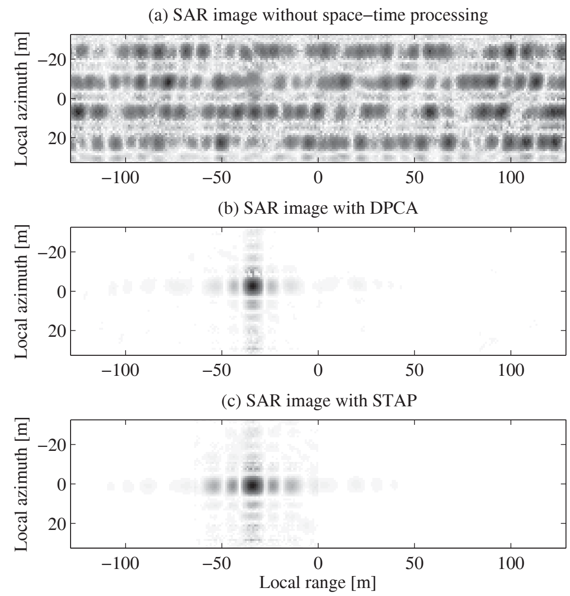

Fig. 4. SAR image of the moving object reconstructed from the beams with and without space-time processing. (a) no space-time processing, (b) DPCA processing, (c) STAP processing.

are formed separately before stacked into the column vector $\mathbf{z}$. The subtraction in DPCA is performed by (6) where the weighting vector to perform this subtraction $\mathbf{w}_m$ is given by (7). An example of the space-time beams formed by the dual-channel SAR data with DPCA is plotted in Fig. 3.b. If the detection threshold is set, for example $\Lambda = -6$ dB, the moving object is detected. The image of the moving object, a point-like scattering, is reconstructed from these space-time beams and shown in Fig. 4.b. The noise can be seen clearly in the SAR image. This can be explained by the subtraction in DPCA which also subtracts a part of the signal, especially for slow moving targets such as boat, ferry or ship.

In the next demonstration, STAP is implemented on the same dual-channel SAR data but we do not need to delay the forward-channel like DPCA. For demonstration purposes, the signal behavior and the clutter plus noise covariance matrix estimation are not discussed. We assume that such knowledge is available. The beams are also stacked and form the column vector $\mathbf{z}$. The space-time beams are found from (5), however, the optimum weights $\mathbf{w}_m$ is estimated by (1). Fig. 3.c sketches an example of the space-time beams formed by the dual-channel SAR data with STAP. Since the knowledge of the covariance matrices is available, the ground clutter and noise are almost completely suppressed. The moving object can be detected with the same detection threshold $\Lambda = -6$ dB. The SAR image of the object is shown on Fig. 4.c.

6. CONCLUSION

In this paper, we present a possibility to integrate space-time processing techniques into time-domain backprojection process. DPCA and STAP are two considered space-time taxonomies. Simulated results indicate that the integration offers reliable detection and provides SAR images of the detected moving objects.

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