CLEAN Removal of Ground Clutter in Mobile Passive Radar

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***Abstract*—The paper is focused on Doppler-spread clutter removal in mobile passive radar. The presented algorithm is based on CLEAN technique, which was developed for radio astronomy, but is commonly used for passive radar. The algorithm was designed for application in a passive radar placed on a moving platform and equipped with an array antenna system for surveillance signal reception. The use of multielement antenna allows for the application of a space-time approach for modeling the clutter signal to be used, followed by clutter removal using modeled multichannel signal. In the paper theoretical considerations are accompanied by the results of simulations.**

***Keywords*—PCL, STAP, GMTI, CLEAN**

I. Introduction

Ground-based passive radars are now entering a stage of maturity, and related theory seems to be well developed. A number of papers e.g. [1], [2] and a book [3] present details of signal processing algorithms, ranging from digital beamforming [4], to detection based on computation of cross-ambiguity function [5] and reciprocal filters [6], [7]. One of the most important stages in signal processing for passive radar is adaptive clutter cancelation, usually based on adaptive filtering [8].

At the present moment a significant part of research in the field of mobile radars is concentrated on the area of mobile passive radars. As known from active radar history, shortly after designing ground-based active radar engineers and scientists started to work on radars placed on seaborne and airborne platforms. A similar situation can be observed nowadays, as scientists are focused on airborne passive radars [9] working in surveillance [10, 18, 19, 20] and SAR [11] modes.

Up to now the biggest problem has been with effective ground clutter cancelation. Application of DPCA [12] and classical STAP [13], [14] algorithms have not been fully effective, as the assumption of the stationarity of illuminating signals is not met [12, 17].

The CLEAN technique developed for radio astronomy is based on precise modeling strong components of the signal and subtracting them in order to reveal hidden weaker components. The paper presents the CLEAN technique [15] application of Doppler-spread clutter cancelation in mobile passive radar in order to reveal weaker moving target echo. For the sake of simplicity, a 2D case is analyzed, however, the results can be extended to the 3D case.

II. Signal Model

It is assumed that the mobile passive radar is equipped with an antenna array with N receiving channels Rx_n and is mounted on a platform which is moving with constant velocity v_p (see Fig. 1). The non-zero velocity of the platform leads to additional Doppler shift and, as a consequence, to bistatic velocity offset, which appears also for non-moving scatterers.

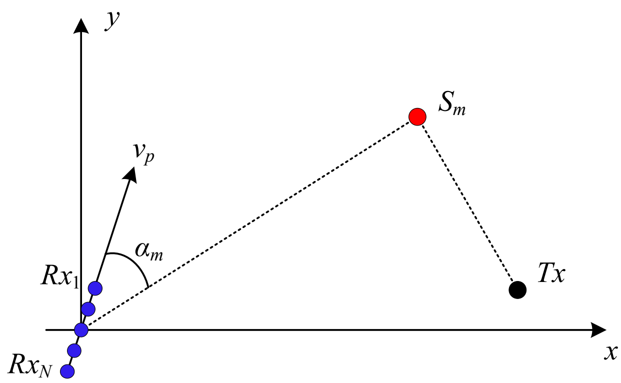

Fig. 1. The considered radar geometry for single clutter scatterer S_m.

In the analyzed model the scene is illuminated by a ground-based transmitter Tx (an opportunity source of illumination), however the formulas can be adapted to other

The work was performed under the statutory research funding of the Faculty of Electronics and Information Technology
978-1-7281-1679-2/19/$31.00 ©2019 IEEE

configurations. The transmitted RF signal which is received by the reference antenna or antennas can be modeled as:

$$x_T(t) = \Re\{X_T(t)\exp(j2\pi f_c t)\}\ . \tag{1}$$

where $X_T(t)$ is a complex baseband information signal, and f_c is the carrier frequency of the RF signal.

The scene echo signal (called surveillance signal in passive radar community) registered by each channel $X_{R,n}(t)$ can contain echoes from stationary scatterers (clutter) $X_{c,n}(t)$ and from the moving targets $X_{t,n}(t)$ as well as noise $W(t)$ which is assumed to be Additive White Gaussian Noise (AWGN):

$$X_{R,n}(t) = X_{c,n}(t) + X_{t,n}(t) + W(t)\ . \tag{2}$$

In the presented model, it is also assumed that the clutter components can be modeled as the signal return originated from a set of single point-like scatterers, which contribute to the scene at different bistatic ranges and different angles. The baseband signal component received by the n-th channel is the sum of time- and Doppler-shifted components related to each clutter scatterer and can be expressed as:

$$\begin{aligned} X_{c,n}(t) = \sum_m A_m \exp\left(-j2\pi f_c \frac{r_{m,n}}{c}\right) X_T\left(t - \frac{r_{m,n}}{c}\right) \times \\ \exp\left(j2\pi \frac{v_p \cos\alpha_m}{\lambda} t \left(t - \frac{r_{m,n}}{c}\right)\right) \exp\left(-j2\pi \frac{l_n \cos\alpha_m}{\lambda}\right), \end{aligned} \tag{3}$$

where A_m is the complex amplitude of the received signal reflected from the m-th scatterer, r_m is the bistatic range of the m-th scatterer from the center of the antenna array, $r_{m,n}$ is the bistatic range of the m-th scatterer from n-th antenna element, c is the speed of light, λ is the illuminating signal wavelength, α_m is the angle between the platform velocity and the scatterer S_m line of sight, l_n is the distance of n-th antenna element from the center of the antenna array.

In passive radar the first step in target detection is the creation of a range-velocity map (surface), which is a function of the bistatic range r and bistatic velocity v. Local maxima of this map are declared as targets. In the considered radar, a series of maps are created – one for each receiving channel n:

$$Y_n(r,v) = \int_0^{\Delta T} X_{R,n}(t) X_T\left(t - \frac{r}{c}\right) \exp\left(j2\pi \frac{v}{\lambda}\left(t - \frac{r}{c}\right)\right) dt\ . \tag{4}$$

where ΔT is the integration time. However, the maps obtained for different channels are different because of the different location of subsequent antennas in the array.

III. CLEAN-BASED DOPPLER SPREAD CLUTTER CANCELATION

The main goal of the presented method is the detection of a weak moving target echo in the presence of strong ground clutter. The proposed method is based on the CLEAN approach [15]. The main idea is to estimate the clutter return $X_{c,n}(t)$ described by (3) and then to subtract it from the received signal $X_{R,n}(t)$ (2). After subtraction the cleaned signal $Xe_{R,n}(t)$ will be obtained, ideally consisting of the target return and thermal noise only:

$$Xe_{R,n}(t) = X_{t,n}(t) + W(t)\ . \tag{5}$$

To achieve this, a set of unknown coefficients A_m must be estimated. Therefore, the first stage of the algorithm is focused on the estimation of the clutter parameters. The direct estimation of coefficients A_m is a complex task. One of possible approaches is the application of sparsity-based algorithms [16] which, however, will be computationally very costly. In the proposed solution the coefficient A_m will not be estimated directly, but instead the clutter coefficient in bistatic range – bistatic velocity grid will be estimated.

To obtain the information of the clutter scatterers on the scene, the signals from subsequent channels should be combined in such a way that the bistatic velocities of clutter scatterers (corresponding to a stationary scatterer with velocity equal to zero) are the same. This means that the information about the relative position of subsequent antennas should be properly taken into consideration as in digital beamforming, which results in summing the range-velocity maps (4) with different coefficients corresponding to the antenna positions:

$$Y(r,v) = \frac{1}{N}\sum_{n=1}^{N} Y_n(r,v) \exp\left(j2\pi \frac{l_n}{\lambda}\frac{v}{v_p}\right), \tag{6}$$

which produces the first estimate of the clutter scene in bistatic range-bistatic velocity coordinates.

Let the clutter scene be defined in bistatic coordinates as $C(r,v)$ which is the projection of A_m on the bistatic plane. The matrix $Y(r,v)$ calculated by (6) can be treated as a convolution of the clutter scene $C(r,v)$ and the ambiguity function of illuminated signal $X_T(r,v)$

$$Y(r,v) = C(r,v) \otimes X_T(r,v)\ , \tag{7}$$

where

$$X_T(r,v) = \int_0^{\Delta T} X_T(t) X_T\left(t - \frac{r}{c}\right) \exp\left(j2\pi \frac{v}{\lambda}\left(t - \frac{r}{c}\right)\right) dt \quad \square$$

In the frequency domain, equation (7) can be expressed as the Fourier Transform of $Y(r,v)$ equal to multiplication of Fourier Transform of the scene $C(r,v)$ and the Fourier Transform of the reference signal $X_T(r,v)$.

$$FT[Y_c(r,v)] = FT[C(r,v)] FT\left[X_T(r,v)\right]. \tag{9}$$

The scene estimation $\widehat{C}(r,v)$ can be obtained by solving (9), and the simplest estimator will have the following form

$$\widehat{C}(r,v) = FT^{-1}\left\{\frac{FT\left[Y(r,v)\right]}{FT\left[X_T(r,v)\right]}\right\}, \tag{10}$$

where FT^{-1} denotes the inverse Fourier transform. The direct implementation of (10) can be unstable, as the problem of division 0/0 or by very small values can arise. Several techniques can be used to avoid such a problem, but due to the limited space of the paper they will not be discussed here.

Having the clutter estimated, (10) the CLEAN approach can be used to cancel the clutter scatterers from the range-Doppler map calculated for a given receiving channel:

$$Y_{clean,n}(r,v) = Y_n(r,v) - \hat{Y}_n(r,v)\,. \qquad (11)$$

where $\hat{Y}_n(r,v)$ is the crossambiguity function calculated for the n-th element of the antenna array, estimated scene $\widehat{C}(r,v)$ and illuminating signal $X_T(t)$.

The method described above does not cancel the moving targets, as was confirmed in the performed simulation investigations, the selected results of which are presented in the next section.

IV. Simulation Results

To verify the presented methods, intensive simulations were performed. In Fig. 2 an example scene is presented.

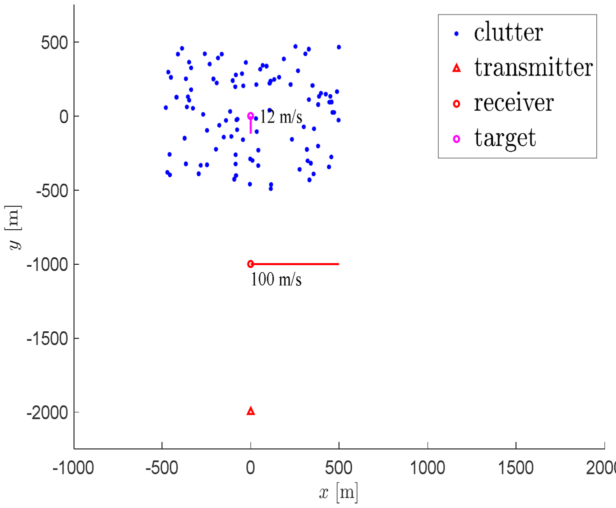

Fig. 2. Simulation scene.

The receiver antenna is composed of a 7-element uniform linear array (the elements are omnidirectional). The distance between two consecutive receiving elements (radiators) is equal to half of the wavelength. The carrier frequency is equal to 634 MHz and the bandwidth of the signal used in the simulations is equal to 7.6 MHz. These parameters correspond to DVB-T channel 41.

The number of point scatterers is 100 and their position in x-y coordinates are generated randomly with a uniform distribution on the square (-500, -500), (500, 500) [m]. The transmitter is located at position (0, -2000). The radar is placed on a moving platform at position (0, -1000) and its speed is equal to 100 [m/s] ((100, 0) in vector representation).

Additionally, a single moving target is embedded in the clutter at location (0, 0) with speed 12 m/s (0, -12), much lower than the speed of the platform and thus it is expected that the target return will be hidden in the ground clutter. The input target signal SNR was set to 10 dB. As the integration gain is at the level of 50 dB noise is not visible on the presented figures, as the main idea of the paper is to shown the ability of presented method for clutter cancelation.

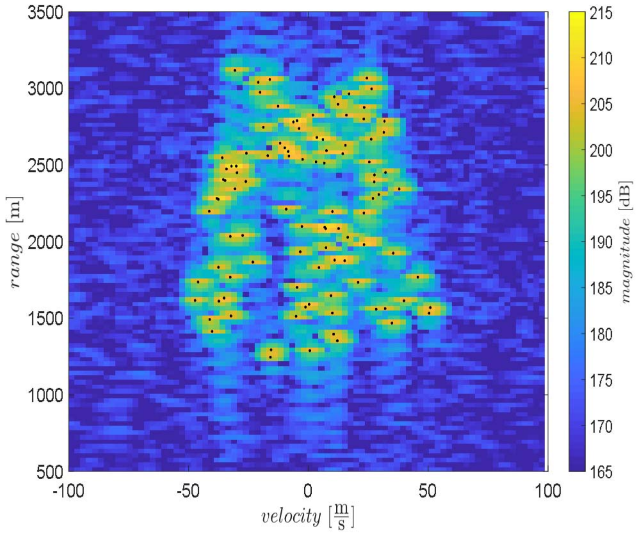

Fig. 3. Cross ambiguity function of simulated signals for single antenna.

The results of the cross-ambiguity function calculation according to (4) is presented in Fig. 3. As was predicted, the ground clutter completely masked the target return.

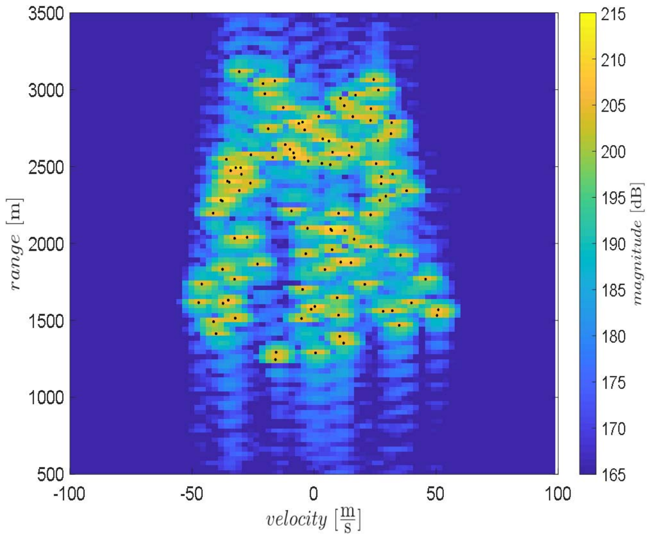

Fig. 4. Estimated scene using the presented method.

The clutter scene estimated by the proposed method (10) is presented in Fig. 4. It is worth mentioning, that the scene is similar to the ambiguity function presented in Fig. 3 but the far sidelobes are reduced significantly. As can be seen, the near sidelobes are still present, so further improvement of the method is still needed.

After the cancelation of the clutter using the CLEAN approach, one can obtain the result as presented in Fig. 5.

The moving target is clearly visible at bistatic coordinate (R=2000 m, V=24 m/s), which is consistent with the position of the target, as the bistatic coordinates in the presented geometry are the target range and velocity related to passive radar multiplied by 2.

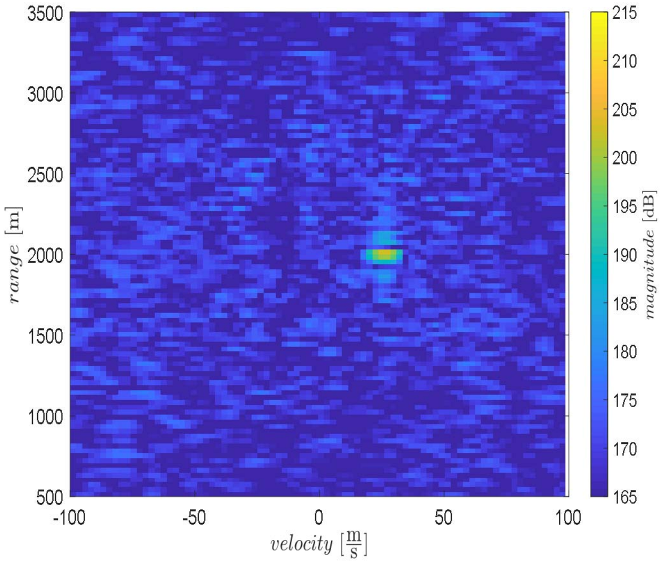

Fig. 5. Cross ambiguity function after CLEAN procedure for single antenna.

The target echo on angle-velocity plot is presented in Fig. 6. The target is clearly visible, but due to rectangular window, applied for processing in all directions (velocity and angular) the high sidelobes of the target are clearly visible. It is worth mentioning that ground clutter was canceled completely by proposed method.

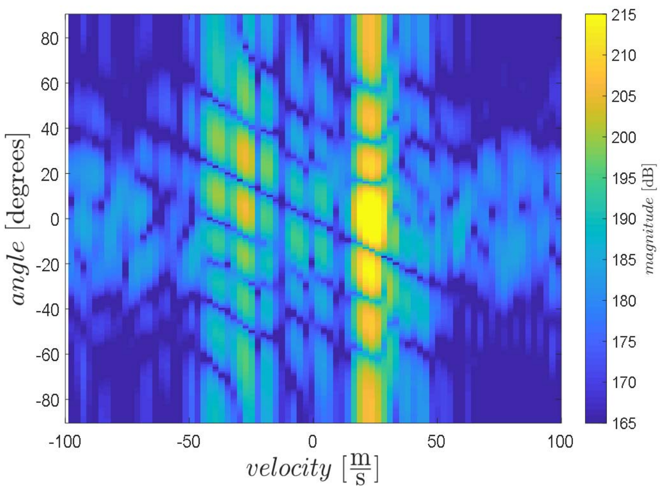

Fig. 6. Velocity – aspect angle map after clutter cancellation and beamformig.

V. Summary

The paper presents a novel CLEAN-based approach to clutter cancelation in mobile passive radar. The simulations show the ability of the algorithm for perfect clutter cancelation, however the cancelation of the noise floor is limited. Further works will be focused on the reduction of the noise floor, application of different windowing method and the experimental validation of the proposed method.

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