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# Objects Classification and Clutter Types Mapping using Polarimetric Radar Detection Algorithms

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***Abstract:*** *Starting from numerical simulation and comparative analysis of different polarimetric detector algorithms using the proposed Gain of Detectability measure, this paper has validated the feasibility and accuracy of polarimetric detectors in scenarios with homogeneous clutter. These algorithms' application to real radar data with non-homogeneous clutter also shows that detection quality can be seriously improved using detectors that use a priori knowledge of the expected target and clutter polarimetric characteristics. A new application of the Polarimetric Whitening Filter and the Optimal Polarimetric Detector for the classification/mapping of targets and ground-based clutter has been proposed and demonstrated.*

## 1. Introduction

Radar target detection in heavy clutter is still an acute problem for modern surveillance radars. One of the main challenges is that ground-based clutter is usually characterized by high spatial variability. One of the possible solutions is to improve the radar contrast between the target and the surrounding clutter using the difference in their polarization parameters.

Target detection methods based on polarization information can be divided into two classes. The first set includes a few detection algorithms [1], [2], that use different ways for the polarimetric radar channels fusion with a goal to make the target echo in the received signal stronger than the noise and/or clutter. Another set includes algorithms for the polarimetric statistical detection [3], [4], [5]. The main idea of these algorithms is to establish a reliable polarization information model of the target, noise, and/or clutter, and realize target detection based on statistical decision criteria. In most previous studies, all these polarimetric detection algorithms were developed and tested/operated for target detection in spatially homogeneous clutter with reasonable intervals of radar ranges and azimuths. However, in the real-world scenario, the ground-based clutter is usually quite non-homogeneous in space. The aim of the research in this paper is to use polarimetric information for target detection in a realistic scenario with heavy spatially non-homogeneous clutter and to estimate their performances in such non-trivial conditions. Based on the S-band polarimetric-Doppler FMCW PARSAX radar [6], this research has studied the spatial variability of polarimetric characteristics of the recreation area in the Delft city surroundings, and has validated polarimetric detection algorithms' applicability to the real radar scene with highly spatially non-homogeneous clutter.

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The paper is organized as follows. In chapter 2 the overview of six analyzed polarimetric detection algorithms is given together with the model of targets and clutter polarimetric characteristics that were used for theoretical comparative analysis of algorithms' performances. There also presented a new proposed measure for the algorithms performance comparison - the Gain of Detectability. Chapter 3 describes the real polarimetric radar measurements of the targets in non-homogeneous ground-based clutter and the resulting data pre-processing steps. Chapter 4 shows the results of the applicability of the polarimetric detection algorithms to real data and their applicability for target identification and radar clutter classification/mapping using *a priori* information. Finally, the conclusions are drawn in Section 5.

## 2. Target detection using polarimetric information

In this paper, the comparative analysis of the proposed in the previous studies ([1], [2], [7], [9]) polarimetric detection algorithms' performances are done in terms of the gain of detectability, with the goal to perform the validation of the developed and implemented polarimetric radar simulator, which generates the feature vectors using the covariance matrix-based statistical description of the radar-observed objects.

### 2.1. Polarimetric Detection Algorithms

Target detection methods based on polarimetric information can be mainly categorized into two classes. The first set is the polarimetric detection algorithms based on the simple fusion of polarimetric channels, which include the single channel detector, span detector, and the Power Maximization Synthesis (PMS) detector.

**The single channel detector** is the simplest for implementation polarimetric detector. It only takes into consideration the single polarimetric channel's magnitude information and can achieve target detection in the case where the observed target has a significant cross-section with a stronger backscattering than that of the surrounding clutter. For instance, if $S_{HH}$ denotes the signal that is measured in $HH$ polarization channel, the single channel $HH$ detector compares its intensity with the detection threshold $T$: $|S_{HH}|^2 > T$.

The span of the scattering matrix $\mathbf{S}$ is the total received power in all polarization channels. **The span detector** compares the span of the signal under test with the detection threshold $T$ [1]. In this paper, we suggest the monostatic radar configuration that is characterized by the equality of cross-polarized elements of the polarization scattering matrix. In case of independently measured cross-polarized channels $S_{HV}$ and $S_{VH}$, their averaging $S_{HV} = (S_{HV} + S_{VH})/2$ can be used. Therefore, the span detector's decision rule can be written as $span = |S_{HH}|^2 + 2|S_{HV}|^2 + |S_{VV}|^2 > T$. The use of total power information in such detection can help to avoid missed detections and false alarms.

**The Power Maximization Synthesis** (PMS) detector uses a function of all components of the polarisation scattering matrix that takes into account crosselement relations and is, actually, the improved version of the span detector [1]: $|S_{HH}|^2 + 2|S_{HV}|^2 + |S_{VV}|^2 + \sqrt{\left(|S_{HH}|^2 - |S_{VV}|^2\right)^2 + 4|S_{HH}^* S_{HV} + S_{VV} S_{HV}^*|^2} > 2T.$

The main idea of another set of polarimetric detection algorithms is based on statistical approaches usage. This class of methods contains the Polarimetric Whitening Filter (PWF), the Optimal Polarimetric Detector (OPD), and the Identity-Likelihood-Ratio-Test (ILRT).

The polarization scattering matrix characterizes the instant polarimetric characteristics of the object and does not describe the situation where these characteristics is changing randomly in time and/or space. For such cases, the polarimetric covariance matrix is an essential and common way to analyze the statistical characteristics of objects polarimetric characteristics:

$$\mathbf{C} = \begin{bmatrix} \left\langle |S_{HH}|^2 \right\rangle & \langle S_{HH} S_{HV}^* \rangle & \langle S_{HH} S_{VV}^* \rangle \\ \langle S_{HV} S_{HH}^* \rangle & \left\langle |S_{HV}|^2 \right\rangle & \langle S_{HV} S_{VV}^* \rangle \\ \langle S_{VV} S_{HH}^* \rangle & \langle S_{VV} S_{HV}^* \rangle & \left\langle |S_{VV}|^2 \right\rangle \end{bmatrix} \tag{1}$$

**The Polarimetric Whitening Filter** (PWF) was proposed to detect targets in the spatially homogeneous clutter environment in the case when the clutter's statistical characteristics represented by its covariance matrix $\mathbf{C_c}$ are known *a priori* [7]. The PWF firstly passes the polarimetric measurement vector $\mathbf{X} = [S_{HH}\ S_{HV}\ S_{VV}]^T$ through a whitening filter that makes the clutter look like a "white", non-correlated noise, and then sums the powers contained in the elements of the vector [8]: $\mathbf{X}^\dagger \mathbf{C_c}^{-1} \mathbf{X} > T$

In general, the detection of a target in the homogeneous clutter case can be formulated as a problem for testing two hypotheses: $H_0$ that in the analyzed signal only the clutter and noise are presented, and $H_1$ that the target echo is added to the clutter and noise mixture. **The Optimal Polarimetric Detector** (OPD) was designed to test these two hypotheses using a likelihood ratio test with consideration of known clutter's and target's statistics [9]. The formulation of this likelihood ratio creates the OPD algorithm [9]:

$$\mathbf{X}^\dagger \left( \mathbf{C_c^{-1}} - \mathbf{C_{t+c}^{-1}} \right) \mathbf{X} + \ln \frac{|\mathbf{C_c}|}{|\mathbf{C_{t+c}}|} > \ln T.$$

where $|\mathbf{C_c}|$ and $|\mathbf{C_{t+c}}|$ stand for the covariance matrices determinants in cases of clutter and target + clutter, respectively. In an ideal case, the OPD algorithm requires *a priori* knowledge of the covariance matrices of the target and the clutter that results in the reduction of false alarms and missed detection, in the best detection performances.

**The Identity-Likelihood-Ratio-Test** (ILRT) was proposed as an alternative to the OPD [1], replacing the target covariance matrix with a scaled identity matrix:

$$\mathbf{X}^\dagger \left[ \mathbf{C_c^{-1}} - \left( \frac{1}{4} E\left[ span(\mathbf{X_t}) \right] \cdot \mathbf{I} + \mathbf{C_c} \right)^{-1} \right] \mathbf{X} > T$$

where $\mathbf{I}$ is the 3-by-3 identity matrix, and $E\left\{ span(\mathbf{X_t}) \right\}$ denotes the expected span of the target return $\mathbf{X_t}$, which is the mean value of the total power of the target in the all polarization channels.

## 2.2. Model of the Polarimetric Radar Signals

The second set of described above polarimetric detectors requires *a priori* knowledge of covariance matrices for clutter and targets. For the theoretical analysis of algorithms' performances were proposed polarimetric models of clutter and targets. In this study, the complex-Gaussian clutter covariance matrix was modeled using the following form [9]:

$$\mathbf{C_c} = \sigma \begin{bmatrix} 1 & 0 & \rho\sqrt{\gamma} \\ 0 & \epsilon & 0 \\ \rho^*\sqrt{\gamma} & 0 & \gamma \end{bmatrix} \tag{2}$$

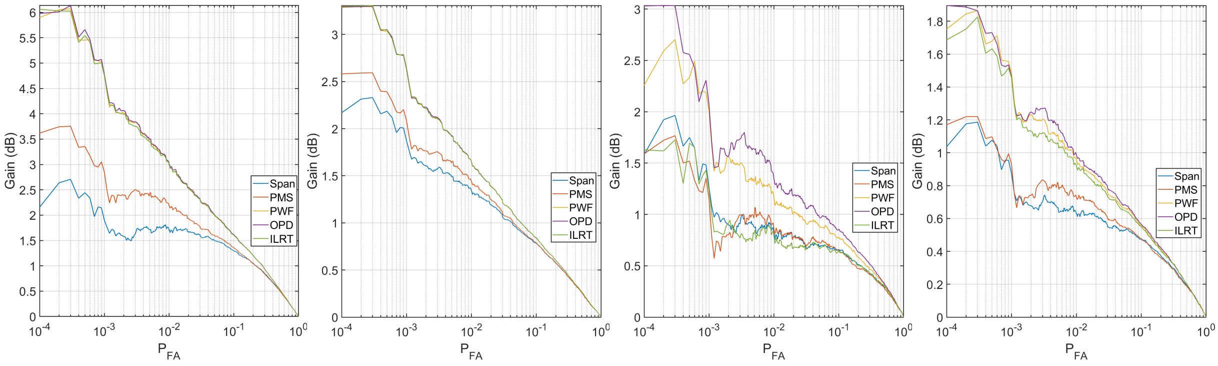
where $\sigma$ denotes the backscattering power in the $HH$ polarization channel, $\epsilon$ is the powers' ratio of $HV$ and $HH$ returns, $\gamma$ - the powers' ratio of $VV$ and $HH$ polarizations, and $\rho$ denotes the correlation coefficient between received signals at $HH$ and $VV$ polarizations.

Depending on the target's size and the radar resolution settings, a specific radar target can be modeled as a distributed (multi-scatterers) object or as a simple pointed deterministic object. For the radar system with medium- or high-resolutions, the multi-scatterers targets can be described using the presented above polarimetric clutter model (2). In the polarimetric radar signal simulator that was developed and used in this study, the polarimetric feature vectors $\mathbf{X}$ for clutter and multi-scatterer target were generated based on the multiplication of $3 \times 1$ vector of independent Gaussian complex signals with the Cholesky decomposition of the expected covariance matrices. For the case of a low/medium-resolution radar, when the target can be presented as a deterministic point object, the polarimetric vector can be written as $\mathbf{X} = \alpha \cdot \begin{bmatrix} \cos 2\theta & e^{j\phi}\sin 2\theta & -e^{j2\phi}\cos 2\theta \end{bmatrix}^T$ [1]. Here $\alpha$ denotes the scale of backscattering intensity of the polarization channels, $\theta$ specifies the orientation angle of the target, and $\phi$ - the phase shifts between channels. For two simple targets that are widely used for radar performance analysis and calibration, these parameters are equal to ($\theta = 0, \phi = \pi/2$) for the trihedral reflector, and ($\phi = 0$) for the dihedral reflector with the orientation angle $\theta$.

## 2.3. Gain of Detectability

To display and analyze a target detection algorithm's performance, the conventional ROC curve is widely used to choose the threshold cut-off points. This curve represents a relation between the probability of target detection $P_D$ and the probability of false alarm $P_{FA}$, characterizing the ability of an analyzing algorithm to distinguish the $H_1$ hypothesis (radar return with a target) from a 'negative' $H_0$ hypothesis (radar return without a target). To validate the correctness of the developed within this study polarimetric radar signals simulator and to study comparatively the efficiency of the listed above polarimetric detection algorithms, ROC curves that were published in [1], [10], [11], [12], [13] have been reproduced for the same target's and clutter's parameters as in original publication.

As an advanced tool for the comparative analysis of multiple detection algorithms' performances, this paper proposes to estimate and visualize **the gain of detectability** for any specific



(a) AT, $TCR = 6$dB (b) AT, $TCR = 10$dB (c) Truck, $TCR = 6$dB (d) Truck, $TCR = 10$dB

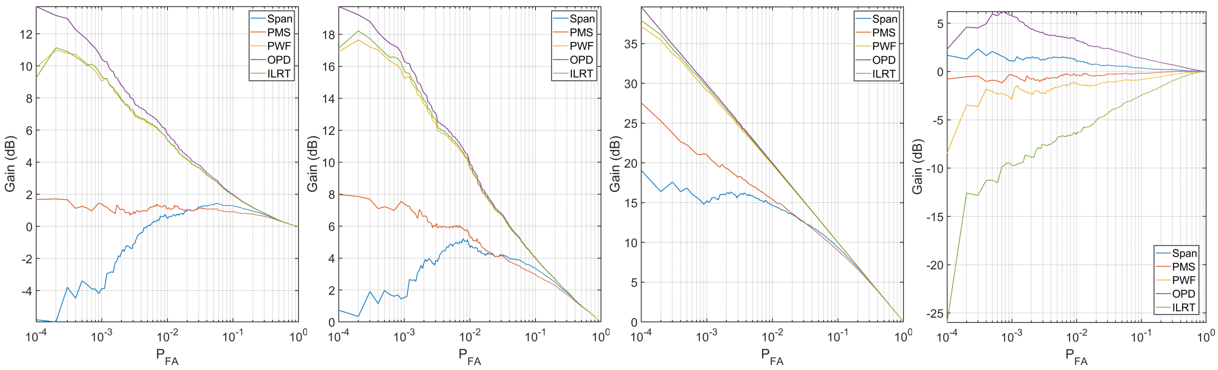
Figure 1: Gain of detectability for multi-scatterers targets (AT - Armored target)

detection algorithm in relation to some selected reference algorithm. In this paper, it is defined as a ratio of the probabilities of detection for specific and reference algorithms, for the fixed rate of false alarms. As the reference within this study has been used the single channel detector:

$$Gain = \left. \frac{P_D(\text{span, or PMS, or PWF, or OPD, or ILRT})}{P_D(HH)} \right|_{P_{FA}=const} \tag{3}$$

For a better representation of the gain's wide dynamic range, it is converted to decibels, and higher positive values indicate that the polarimetric detectors have more effective performance for the detection of a target in clutter than the single channel detector. Apart from the difference in polarization parameters, the target-to-clutter ratio $TCR$ is also influencing the detection result. The $TCR$ can be defined as the ratio of total powers that are received from target and clutter: $TCR = E\left\{span\left(\mathbf{X}_t\right)\right\}/E\left\{span\left(\mathbf{X_c}\right)\right\}$ [1]. Here $E\left\{span\left(\mathbf{X}_t\right)\right\}$ and $E\left\{span\left(\mathbf{X}_c\right)\right\}$ are the expected span of the target and clutter returns, respectively.

The results in Figures 1a – 1d correspond to the case of complex (distributed) targets with multiple scatterers (armored target and truck) detection in the homogeneous clutter with the



(a) DHR, $\theta = 0°$, $TCR = 3$ dB (b) DHR, $\theta = 22.5°$, $TCR = 3$ dB (c) DHR, $\theta = 45°$, $TCR = 3$ dB (d) THR, $TCR = 3$ dB

Figure 2: Gain of detectability for point targets (DHR - dihedral, THR - trihedral reflectors)

target-to-clutter ratio equal to 6 and 10 dB. For high probabilities of false alarms, the gain for all algorithms expectedly approaches the value of 0 dB. For the effective detection with the low $P_{FA}$ values, the PWF and OPD detection algorithms both show impressive (a few times) improvements in terms of the gain in the detection probability in comparison to the single channel detector. At the same condition, the span and PMS detectors show only a slight increase in the detection probability in comparison with the reference single-channel detector. For the typical deterministic point targets – dihedral and trihedral reflectors in the meadow clutter, from Figures 2a – 2c it can be seen that the PWF and OPD polarimetric detectors also show relatively high values of the gain in target's detectability (more than 10 times) than the reference single channel detector and similar span and PMS algorithms. The detection of the trihedral reflector with all types of detectors shows the worst case with the minimum efficiency of the polarimetric information usage as soon as this target has quite similar to clutter polarimetric characteristics. In addition, the ILRT method for all analyzed cases shows quite low levels of gain and irregular behavior due to the difference in its basic assumption and real targets' characteristics. This method will not be further discussed within the analysis of measured real data.

## 3. Polarimetric Radar Measurements of the Non-homogeneous Ground-based Clutter

The radar observation of different objects in the real non-homogeneous ground-based clutter has been done using the azimuthal scan of the recreation area near Delft, the Netherlands, with the polarimetric S-band PARSAX radar [6]. The measured data have been geo-referenced and fitted to the Google Earth image as shown in Fig. 3 for the $HH$ channel amplitudes. As a set of quasi-pointed targets was selected the set of power-line masts that are located on the map in a straight line. The ground-based clutter in this scene includes areas of grasslands, forests, farm buildings, and other constructions. To carry out the target detection in the realistic scenario with heavy non-homogeneous clutter, the measurement was done using the high-range resolution ($\Delta R = 3.6$ m) configuration of the PARSAX radar. High-resolution Doppler filtration of the zero-Doppler returns during azimuthal scanning results in complex range profiles of all elements of the polarization scattering matrix with the azimuth resolution of $\sim 0.1°$. The noise

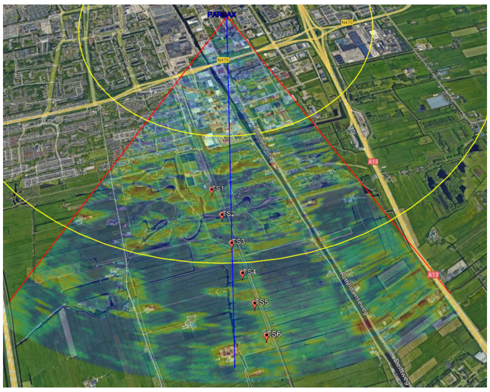


Figure 3: Geo-referenced plan position indicator (PPI) representation of the HH channel data

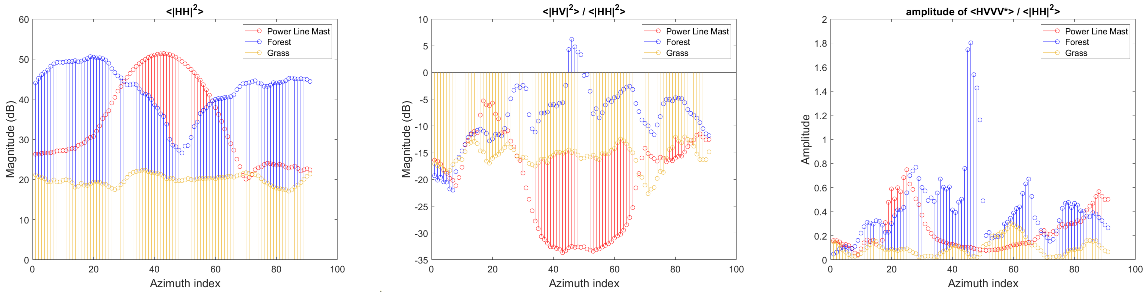
measurement has been used for the polarimetric channels' equalization and calibration [8].

For the estimation of the polarimetric covariance matrices corresponding to every pixel of the observed scene, spatial averaging has been implemented as the moving spatial window averaging algorithm. This algorithm calculates the covariance matrix for a specific point of the range–azimuth map using its averaging within the selected-sized window around this point. Moving this estimation window through all points of the map resulted in the multidimensional map of all elements of the polarization covariance matrix. The implemented size (5 ranges by 7 azimuths) has been chosen based on the compromise between the similarity of the pixels representing the same type of observed objects and the minimal degradation in the spatial resolution to avoid over-smoothing. The resulting map of six elements of the covariance matrix - real $C_{11}$, $C_{22}$, $C_{33}$, and complex $C_{12}$, $C_{13}$, and $C_{23}$, - contains all the polarimetric information, representing intensity and correlation between $HH$, $HV$, and $VV$ polarization channels [8].

An example of the analysis of the reference target and different types of ground clutter statistical characteristics is presented in Fig. 4. These plots show the azimuth cuts of different elements of covariance matrix elements when the range is set to a constant. The $HH$ channel polarization intensity represented by $C_{11}$ is shown in Fig. 4a. It is interesting to notice that the specific covariance patterns of different observed objects are obtained as a convolution with the antenna pattern. As a result, forest and grass areas are wider distributed within the azimuth than the power-line mast. According to these plots, the near-point target occupies around 30 azimuth indexes due to the radar antenna bandwidth. Furthermore, combing the results of different covariance matrix elements such as $C_{22}$ in Fig. 4b and $C_{23}$ in Fig. 4c, the grass area shows the stable similarity of the polarimetric characteristics as a homogeneous clutter, while the forest area can be categorized as non-homogeneous clutter in terms of polarimetric characteristics variation.

## 4. Radar Object Classification

The experimental validation of the efficiency of the listed above polarimetric detection algorithms via their application to the real radar observation of the ground-based non-homogeneous



(a) $C_{11}$ (b) $C_{22}$ (c) $C_{23}$

Figure 4: Covariance matrix elements for the near-point target and two types of the ground clutter

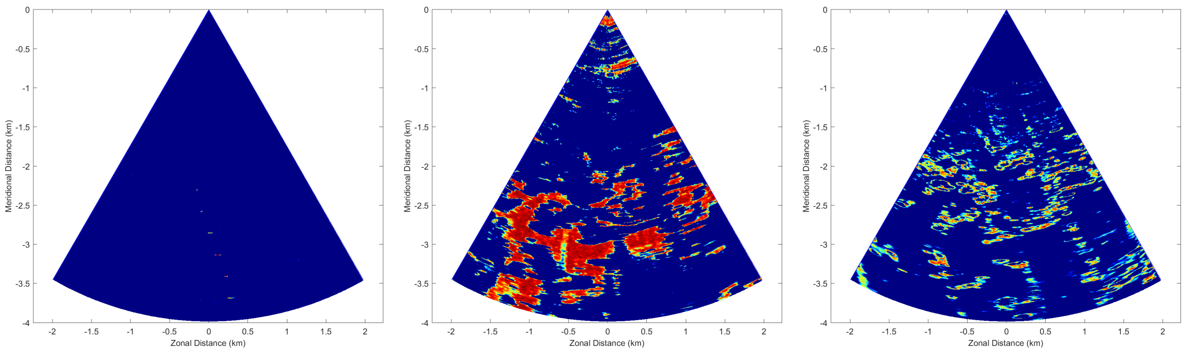
clutter shows a few interesting results.

The class of detection algorithms that uses the simple fusion of polarimetric channels (it includes the single channel detector, the span detector, and the PMS detector) works completely non-effective in the heavy non-homogeneous clutter environment - the application of these algorithms to real data does not result in any improvements in the contrast between the point target of interest and distributed clutter.

In this study the OPD algorithm uses the *a priori* (preliminary-defined) polarimetric covariance matrix of the target (power-line mast) and the spatial moving averaging window algorithm to estimate the clutter's covariance matrix for every location. As shown in Fig. 5a, all six reference targets can be 100% detected in non-homogeneous grass and forest clutter practically without false alarms using *a priori* knowledge of the reference targets at six positions and the right setting of the detection threshold (-10 in this case).

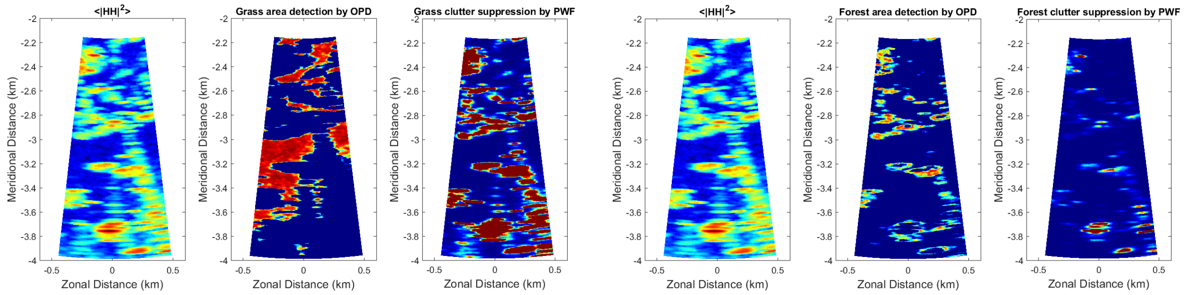
In this research, we proposed and tested the new application of the OPD algorithm for the classification/mapping of (non-)homogeneous ground-based clutter. In this processing, the typical covariance matrices of grass and forest areas are used in the detection algorithms as a matrix of the reference target. As it can be seen in Fig. 5b, the OPD algorithm is a promising method for the grasslands classification, showing for this type of object the detector output level that is significantly stronger than the levels for other objects. Since the polarimetric characteristics of the forest areas are spatially non-homogeneous, the OPD algorithm output for the forest areas classification shows more variability in the output values (see Fig. 5c), which indicates the high sensitivity of the OPD algorithm to the reference target's covariance matrix.

The PWF algorithm shows excellent effectiveness in the suppression of grass and forest clutter. Fig. 6a indicates that the PWF is not very sensitive in terms of similarity between the reference covariance matrix and the matrix at the analyzed spatial location, providing good suppression quality within the wide areas with the same type of clutter. In Fig.6b, the PWF also shows a good suppression of non-homogeneous (forest) clutter.



(a) Power line masts (b) Grass area (c) Forest area

Figure 5: Objects classification by Optimal Polarimetric Detector



(a) Grass clutter (b) Forests clutter

Figure 6: Clutter detection by OPD and suppression by Polarimetric Whitening Filter

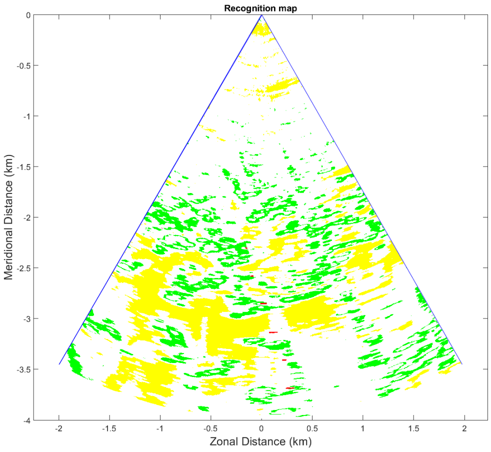


Figure 7: Classification map of the reference targets and types of the ground-based clutter

Finally, with the OPD algorithm all three classes of objects - power-line masts, grass areas, and forest areas, - have been classified and shown on a classification map in Fig.7. This map was created using a simple RGB coding of every class detection output. It shows high efficiency and reliability of the use of the OPD algorithm for the polarimetric classification of observed objects using *a priroi* (predefined) polarimetric characteristics (covariance matrix) of predefined classes. It is important to mention that the OPD algorithm can easily be parallelized for the identification of multiple reference classes of targets and it also can be implemented as a real-time streaming signal processing algorithm.

## 5. Conclusions

The comparative analysis of six polarimetric radar detection algorithms' performances and their sensitivity to the difference in the polarimetric characteristics of target and clutter has been done in this study. This analysis uses the simulated with the developed polarimetric radar simulator data for homogeneous clutter cases, and the real high-resolution radar data for spatially non-homogeneous clutter cases. The new measure, the Gain of Detectability, has been proposed to characterize the potential benefits of polarimetric information usage for target detection. It was demonstrated that the class of detection algorithms that uses the simple fusion of polarimetric channels (it includes the single channel detector, the span detector, and the PMS detector) works completely non-effective in the heavy non-homogeneous ground-clutter environment. At the same time, the Polarimetric Whitening Filter shows very good efficiency in the suppression of clutter with known polarization characteristics. The Optimal Polarimetric Detector can be effectively used for the classification/mapping of the targets and non-homogeneous ground-based clutter using their *a priori* known characteristics. Such classification can be implemented as a real-time streaming signal processing algorithm.

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