Incoherent change detection methods for wavelength-resolution SAR image stacks based on masking techniques

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***Abstract*—This paper presents two incoherent change detection methods for wavelength-resolution synthetic aperture radars (SAR) image stacks based on masking techniques. The first technique proposed is the Simple Masking Detection (SMD). This method uses the statistical behavior of pixels-sets in the image stack to create a binary mask, which is used to remove pixels that are not related to changes in a surveillance image from the same interest region. The second technique is the Multiple Concatenated Masking Detection (MCMD), which produces a more selective mask than the SMD by concatenating multiple masks from different image stacks. The MCMD can be used in specific applications where multiple stacks share common patterns of target deployments. Both proposed techniques were evaluated using 24 incoherent SAR images obtained by the CARABAS II system. The experimental results revealed that the proposed detection methods have better performance in terms of probability of detection and false alarm rate when compared with other change detection techniques, especially for high detection probabilities scenarios.**

I. Introduction

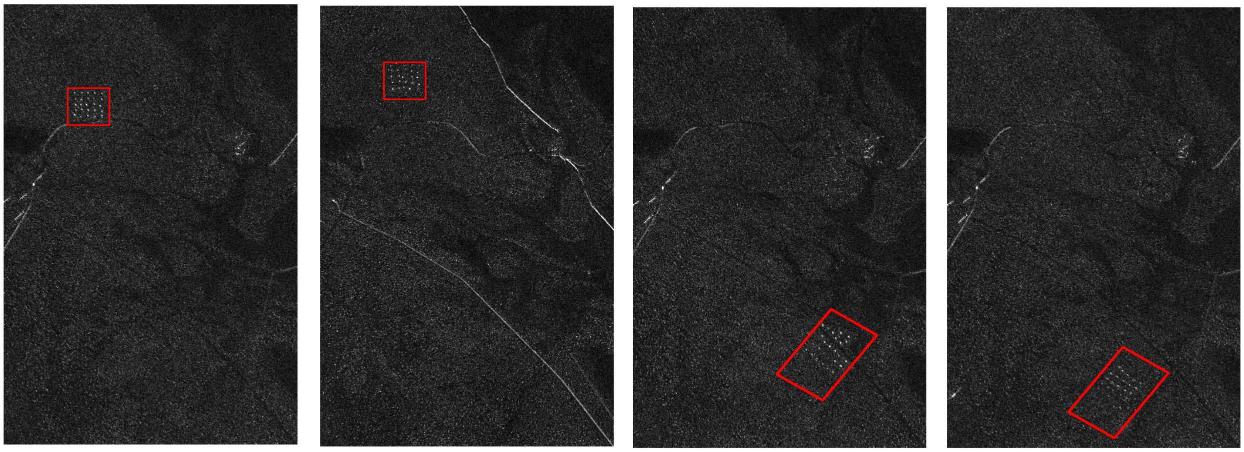
Change detection methods are frequently used for a large set of applications in synthetic aperture radar (SAR) images, such as detection of concealed targets, monitoring of forested areas, or natural disasters [1]–[3]. The usage of this method for SAR images consists of detecting changes between different image measurements for the same ground scene [4]. Among the various SAR systems, the detection of concealed targets in regions with high-density of vegetation is preferably made by Foliage-Penetrating (FOPEN) radars, which usually operate at the very-high frequency (VHF) and ultra-high frequency (UHF) frequency bands. The Swedish SAR system, CARABAS II, is inserted in this context. The CARABAS II system operates in the VHF frequency range (20 - 90 MHz) and is characterized by its large fractional bandwidth and a wide antenna bandwidth [5]. The resolution of SAR systems with these characteristics is on the order of radar signal wavelengths, so these systems are often referred to as wavelength-resolution SAR systems [6], [7].

The usage of wavelength-resolution SAR images for change detection (CD) applications is mainly because FOPEN systems are not sensitive to small objects present in the ground scene. Also, large scatterers tend to be stable in time and not severely affected by the environmental conditions. Thus, this type of system is capable of obtaining highly similar images from the same ground area for different time measurements, considering the same flight geometry [8].

Traditionally, change detection methods for wavelength-resolution SAR are based on likelihood tests considering image pairs [9], [10]. However, the usage of small stacks of images was recently considered to improve the performance of wavelength-resolution SAR change detection techniques [6], [11]. Besides, a statistical test analysis based on image stacks for wavelength-resolution SAR images can be found in [12]. According to the observations presented in [12], the majority of the pixels of a stack of wavelength-resolution SAR images can be modeled as Rician distributed. The authors also observed that the Rician distribution does not yield a good fit for changes present in one or more images of the stack.

Additionally, the binary image outputs presented in [12] share similar characteristics with mask images used in masking techniques [13]. Obtaining and using image masks more effectively is an important research topic for image processing, especially for segmentation applications [14]–[16]. Moreover, masking techniques can also be used in target detection applications [17].

Motivated by the possible gains associated with the use of SAR image stacks in CD methods, by the statistical test analysis presented in [12], and by the use of masking techniques for CD applications, this paper presents two new change detection methods for wavelength-resolution SAR image stacks based on masking techniques. The proposed methods are evaluated using the data set acquired with the CARABAS II system [19], [18]. The experimental results demonstrate that the proposed detection methods have better performance than traditional change detection methods, especially for high detection probabilities scenarios.



(a) (b) (c) (d)

Fig. 1. CARABAS II image samples for (a) Mission 1, Stack 1, and Pass 1 (b) Mission 2, Stack 2, and Pass 2 (c) Mission 3, Stack 3, and Pass 5 (d) Mission 4, Stack 1, and Pass 1. The target deployments of each image are highlighted.

The remainder of this paper is organized as follows. The data set used in this paper is presented in Section II. Section III briefly presents and discusses the adopted statistical test analysis of wavelength-resolution SAR image stacks. Section IV presents the two proposed change detection methods based on masking techniques using image stacks. Section V presents experimental results, evaluations, and discussions regarding the proposed detection methods. Finally, Section VI presents some concluding remarks.

II. Data Description

The data set used in this paper is composed of 24 incoherent wavelength-resolution SAR images, obtained by the CARABAS II system. This data set is provided by FOI and has been made available by the Air Force Research Laboratory (AFRL) in [18]. The images cover the same ground area of 6 km^2 (2 km $\times$ 3 km) with a pixel size of 1 m $\times$ 1 m [19]. The system resolution cell covers an area of approximately 3 m $\times$ 3 m. Additionally, the images are already calibrated, pre-processed, and geocoded.

The images were obtained from a flight campaign held in the military base station RFN Vidsel in northern Sweden in 2002. The ground area of interest is composed mainly of forestry areas, but it also contains lakes, human-made structures, and fields. Also, all the measurements contain 25 testing terrain vehicles (targets), which are classified according to their sizes. More information regarding the flight campaign can be found in [20].

Throughout this paper, it is considered the same image classification as the one used in [19]. For the data set, it was considered four different targets deployments (missions), which are measured using six distinct passes. Also, according to the adopted flight geometries, the data set is divided into three distinct image stacks. Thus, based on the information presented in [19], [20], the images obtained with passes 1 and 3 form Stack 1; while Stack 2 is formed with the images obtained with passes 2 and 4; and the others build Stack 3. Figure 1 provides image samples selected from the four possible target deployments and mentions in which stack they belong.

III. Statistical Test Analysis

The statistical test analysis adopted in this paper is similar to the one presented in [12]. The considered test consists of applying the Anderson-Darling (AD) goodness-of-fit (GoF) test [21] to evaluate samples obtained from the SAR image stacks. The AD test is a nonparametric hypothesis test that aims to determine if a given null hypothesis would be rejected [22].

Similarly to [12], the AD test is used to investigate if a given probability distribution null hypothesis yields a good fit for the given sample data from the CARABAS II image stacks. The statistical test is performed in each pixel position of the images that form one stack, using a test sample composed of pixels from one resolution cell of each image from the stack, which is centered in the test position. Thus, each evaluation considers 9 $\times$ 8 pixels, and it is performed a total of 6 million evaluations per image stack. Finally, to reduce the computational cost associated with this test, the test implementation follows the protocol used in [23].

Based on the results presented in [12], throughout this paper, it is only considered the Rician distribution null hypothesis. The output of the statistical test can be represented as a binary image where the null value indicates a failure to reject the distribution hypothesis; otherwise, the unitary value indicates an AD GoF test rejection of the null hypothesis. Figure 2 represents the output of the statistical test for one of the tested image stacks, where target deployments that can be observed in the binary image are highlighted. For the sake of simplicity, it was only considered a confidence level $\alpha = 0.05$.

As can be observed in Figure 2, and it was stated in [12], the Rician distribution yield a good fit for the majority of the pixels in the image stack. It is possible to observe that the situations where the AD test rejects the Rician null hypothesis are either the ones related to changes (targets) that occur in one or more images, or to isolated pixels, which are mainly related to Type I errors. The change detection methods proposed in this paper are based on this observation, aiming to reduce the occurrence of false alarms.

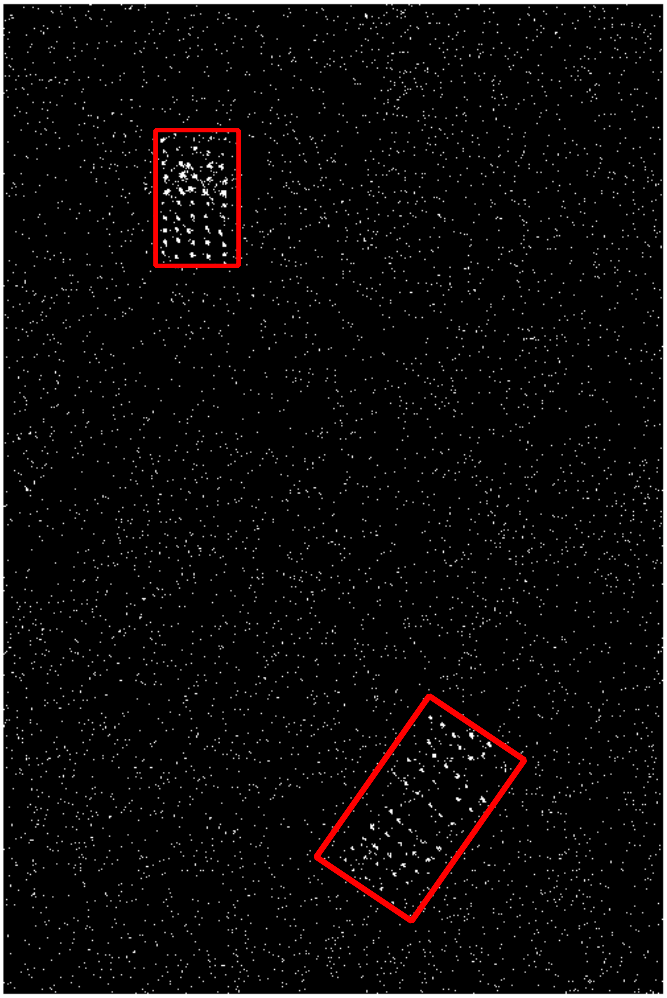


Fig. 2. Example of the statistical test output for an image stack, considering the null hypothesis as Rician. The target deployments that can be observed in the binary image are highlighted.

IV. Change Detection Methods Using Masking

The output of the statistical analysis presented in Section III is a binary image that contains information related to different objects present in the SAR image stack. According to the discussion presented in Section III and in [12], changes in one or more images of the stack can be characterized by an agglomeration of failures in the AD GoF, for a Rician distribution null hypothesis. Thus, based on the characteristics of the output binary image, it is suitable to use it for masking applications. The output binary images obtained by the statistical test presented in Section II are used in the change detection methods proposed in this section.

Both the proposed change detection methods consider the same processing scheme, which only differs in terms of the masking procedure. This processing scheme is presented in Figure 3. The masking procedure is the first block of the processing scheme and can be described as

$$I_u = I_s \circ M, \tag{1}$$

where I_u represents the updated image, i.e., the output of the masking process, I_s is the surveillance image, M is the binary mask image generated with the same dimension as I_u, and the operation ($\circ$) represents the Hadamard product [24].

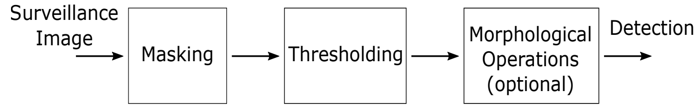


Fig. 3. Simplified block diagram for the proposed change detection methods.

The second block presented in Figure 3 is a detection procedure with a fixed threshold (τ). The output of the block is a binary image where the evaluated pixels with amplitudes above the threshold are represented by unitary amplitude pixels, whereas the other pixels are represented by pixels with null amplitude. Finally, the third block is an optional block composed of morphological operations. These operations are selected according to the methods' application specificity.

A. Simple Masking Detection (SMD)

As previously mentioned, the change detection methods using masking techniques proposed in this paper are based on the statistical analysis and in the observations presented in [12], which are briefly summarized in Section III. In this way, the SMD technique consists of using as a mask the binary output image generated by the statistical test. Thus, for the available CARABAS II data, it is possible to obtain three masks, each one associated with Stacks 1, 2 and 3. Figure 2 presents one example of an SMD mask where the target deployments are highlighted.

It is important to emphasize that, to the correct functioning of the SMD change detection method, the statistical analysis constraints must be respected, such as the use of an appropriate amount of tested pixel samples and the use same flight geometry images. Also, at least one image with the same target deployment as the surveillance image must compound the evaluated image stack. A simple way to fulfill this second requirement, without requiring any prior knowledge about the targets, is to include the surveillance image in the evaluated stack.

B. Multiple Concatenated Masking Detection (MCMD)

The MCMD technique uses as a mask one binary image resulting from a concatenation procedure. This concatenation process is the result of the Hadamard product of all binary image masks obtained using the previously described SMD approach. This mask can be written as

$$M = M_1 \circ M_2 \circ \cdots \circ M_N, \tag{2}$$

where M_i is the i-th mask from the SMD method, $i = 1 \ldots N$, and N is the total number of SMD masks. In this paper, $N = 3$. The MCMD mask for the available CARABAS II data is presented in Figure 4 where the target deployments are highlighted.

Comparing the masks presented in Figures 2 and 4, it is possible to verify that the MCMD mask is more selective than the sample mask from the SMD method. This selectivity tends to lead to a lower occurrence of false alarms. However, it could also lead to a reduction in the target detection probability

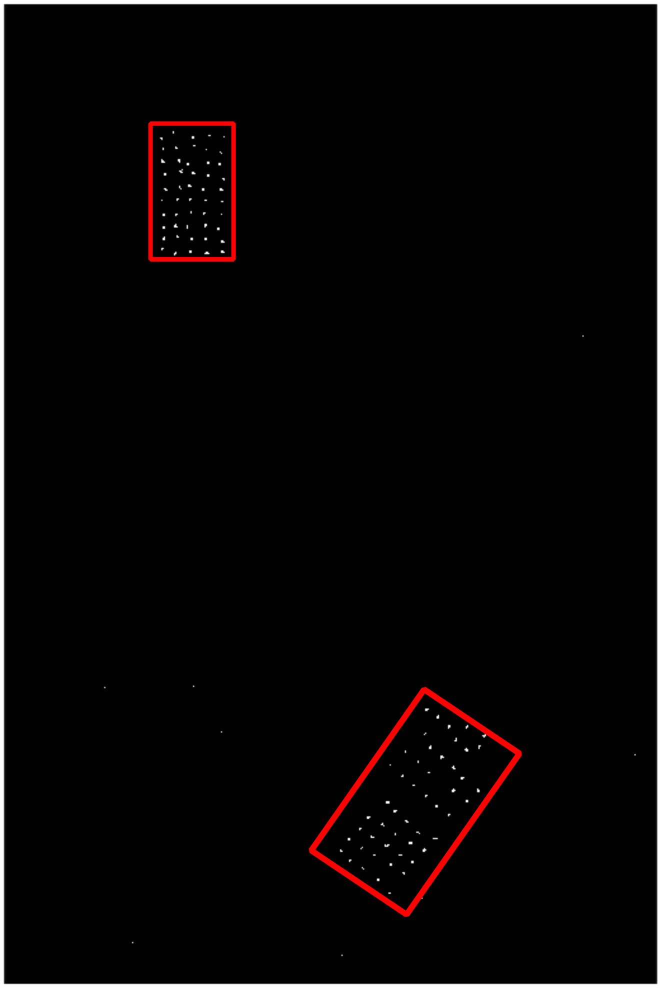


Fig. 4. MCMD mask where the target deployments are highlighted.

caused by the occurrence of missing targets. Besides, to correctly obtain the MCMD mask, the masks used in the concatenation process must contain the target deployment of interest. Thus, the target deployment of the surveillance image must be present in at least one image of each stack used in the masks of the concatenation process. This requirement reduces the number of applications where the method could be used when compared with the SMD method. However, there are still applications where this method can be applied, e.g., image stack applications focusing on fixed targets (concealed structures, land mines, and hidden objects), or image stacks using different flight geometry measurements obtained in short periods.

V. Experimental Results

The experimental evaluation was performed using the 24 incoherent wavelength-resolution SAR images described in Section II, and the proposed change detection methods presented in Section IV. The methods' performance is assessed in terms of the probability of detection (P_d), i.e., the ratio between the number of detected targets and the known number of targets and the False Alarm Rate (FAR), i.e., the number of false alarms per square kilometer. To facilitate the reproducibility of the results, a change is designated to any detected object, even knowing that some of them could be related to image formation issues.

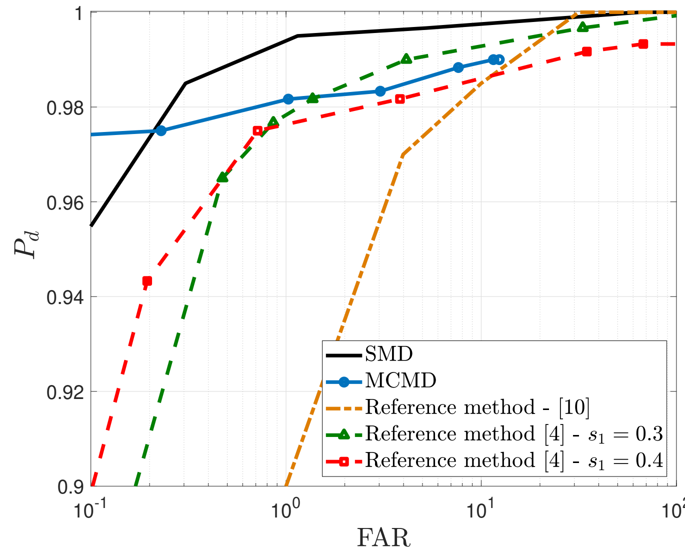


Fig. 5. ROC curves for the proposed methods and the selected reference methods.

It is expected that target-related pixels present higher amplitudes than the majority of the clutter-related ones. Thus, it would be suitable to selected threshold values similar to the expected minimum target amplitudes for this data set, such as the ones considered in [4], $\tau \in [0.2; 0.3; 0.4]$. However, to obtain more points for the Receiver Operating Characteristic (ROC) curves presented in this section, the set of thresholds was extrapolated to a higher number of amplitude values, which lies in the range of [0, 0.6].

It is adopted similar morphological operations like the ones considered in [4], [10], [11], for a fair performance comparison of the results. These operations are one erosion with a squared structuring element with the size of the CARABAS II system resolution cell, followed by dilatations whose size enables the merging of detected objects within a distance lower than 10 m.

Based on the previously described implementation aspects, the first performance evaluation is the ROC curve, which is presented in Figure 5. This evaluation scenario consists of the comparison between the proposed methods based on image stacks and others based on the use of only one reference image. In this analysis, the two selected methods were the ones presented in [10] and [4]. The method presented in [10] was one of the first techniques used to perform change detection in CARABAS II images, whereas the method proposed in [4] has, to the best of the author's knowledge, the best performance for this data set, without considering a SAR image stack scenario. For the sake of simplicity, the notation used in the original papers was kept.

As can be observed in Figure 5, both the SMD and MCMD can achieve high P_d values for low FAR values, which makes them outperform the other methods for the majority of the evaluated points. This performance is achieved by the combination of one selective mask and one erosion operation.

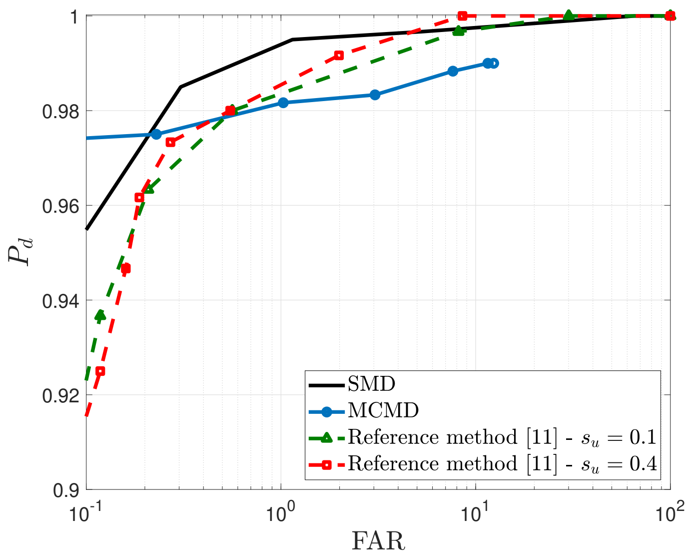


Fig. 6. ROC curves for the proposed methods and the selected reference method.

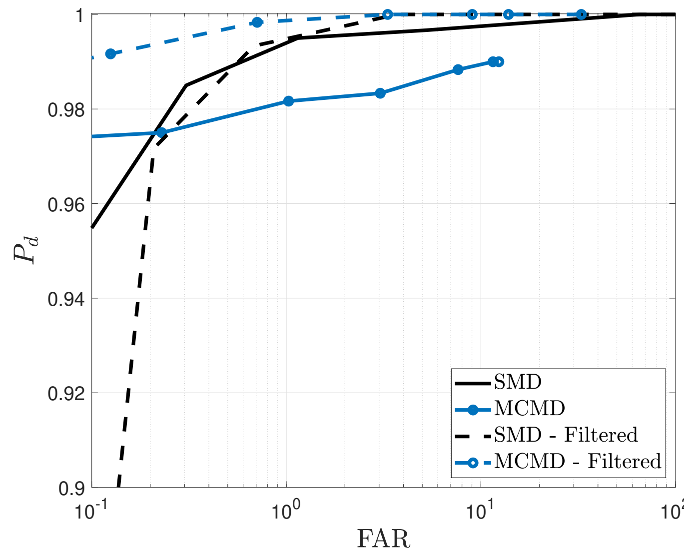


Fig. 7. ROC curves for both proposed methods with/without the use of the pre-processing average filter.

The higher the selectivity of the mask is, the lower will be the number of false alarms. For instance, for a $P_d \approx 0.97$, the SMD method achieves FAR ≈ 0.154, whereas the MCMD achieves FAR $= 0$. However, this combination may also result in targets missing. For instance, the MCMD method is unable to detect six targets resulting in a maximum $P_d = 0.99$ even for $\tau = 0$, which results in the maximum FAR $= 12.37$. Thus, the use of more selective masks tends to jeopardize the method's performance for high detection probability scenarios. Thus, the SMD presents a better performance when compared with the MCMD for $P_d > 0.974$.

The second performance evaluation is presented in Figure 6. This evaluation consists of a comparison between the proposed methods and the method based on SAR image stacks proposed in [11]. To the best of the author's knowledge, the method presented in [11] has the best performance in terms of the evaluated metrics for the tested data set so far. As can be seen in Figure 6, the SMD method outperforms the best performance obtained in [11] for $P_d < 99.6$. Similarly, the MCMD outperforms the best performance obtained in [11] for $P_d < 97.8$.

As previously observed, the combination of a very selective mask and the erosion operation jeopardizes the MCMD performance for high detection probability scenarios. However, it is visible that all the targets are present in the mask shown in Figure 4. Based on this, it is possible to pre-processing the surveillance image to inhibit the erasing of the targets by the erosion operation. Thus, an average filter is applied in the surveillance image with a window size equal to the system resolution cell.

The evaluation of the performance associated with the pre-processing is presented in Figure 7 for the proposed methods. By analyzing the ROC curves, we can observe a performance improvement for the MCMD and SMD methods in high detection probability scenarios. However, it is possible to observe that for lower probabilities of detection, the use of the average filter tends to increase FAR for the SMD method. This effect is directly related to the selectivity of their masks. Thus, the use of a pre-processing scenario seems to be more adequate for very selective masks or when a very high value of P_d is required.

VI. Final Remarks

This paper presented two new incoherent change detection methods for wavelength-resolution SAR using image stacks based on masking techniques. The first method is the SMD, which is based on the use of masks directly generated by the AD GoF statistical test analysis. The proposed method can be used in any test setup, that contains the same target deployment as the image of interest, e.g., the surveillance image is used to generate the mask. The MCMD was the second method proposed. This method uses the concatenation of masks generated by multiple passes resulting in a more selective mask. The application scenarios for this method are more limited than the SMD, since the targets of interest need to be present in all the evaluated images. However, when the constraint is obeyed, the MCMD method tends to result in high probabilities of detection with low false alarms occurrences. Comparisons with other change detection methods were provided, showing that the proposed method can achieve competitive performance in terms of the two evaluated metrics, and outperforming them for the majority of the evaluated scenarios. Both methods were able to achieve a probability of detection of, approximately, 98% for a false alarm rate of only 1 per square kilometer.

Acknowledgment

This work was partially supported by the Brazilian Agencies National Council for Scientific and Technological Development (CNPq), Coordination for the Improvement of Higher Education Personnel (CAPES), by the Swedish-Brazilian Research and Innovation Centre (CISB), and by Saab AB.

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