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COMBINING LEVEL SETS AND ORTHOGONAL TRANSFORM FOR DESPECKLING SAR IMAGES

This paper introduces a new approach for Synthetic Aperture Radar (SAR) image filtering. It combines a Level Set method for heterogeneity region detection and Discrete Cosine or Haar transforms to reduce speckle and preserve small-sized objects (targets). Tests have been conducted on one synthetic and several real SAR data. Furthermore, we present some results on assessing the algorithm with respect to qualitative and quantitative measures. Experiments with simulated and real SAR images have shown that the proposed approach is efficient in speckle filtering while it preserves small-sized objects and texture.

Key words: *one-look SAR image; speckle filtering; Level Set method, DCT, target detection.*

Introduction

Airborne and spaceborne synthetic aperture radar (SAR) imaging sensors are widely used nowadays for different applications [1] due to several advantages. In fact, an SAR imagery system is capable of acquiring data in almost all weather conditions as well as during day and night. Moreover, modern SAR systems are characterized by high spatial resolution that allows exploiting SAR images either separately or in combination with other types of remote sensing (RS) data as, e.g., optical images [2, 3]. These modern systems are mostly multichannel (dual or multi-polarization, multi-frequency) that provides better classification of RS data obtained [4, 5].

Meanwhile, a main problem in SAR imaging is that all obtained data suffer from a noise-like phenomenon called speckle [1, 6] that arises due to coherent processing of received backscattered signals. Speckle is modeled as a multiplicative noise and its distribution does not follow a Gaussian function even if multi-look mode is applied [1, 7]. Additionally, speckle is usually spatially correlated [7, 8] and, hence, this complicates the task of dealing with it [9, 10]. Thus, it is desirable to reduce speckle and multi-look mode of image forming [1] achieves this. However, it causes resolution loss and, hence, SAR imaging partly loses its advantages. Another way of coping with speckle is to apply image filtering (also called despeckling) [1, 6, 7]. Such pre-processing of SAR images makes considerably easier segmentation and classification tasks [1, 4]. Being well designed, SAR despeckling also improves the overall visual aspect of the image and results in an easier analysis and interpretation of the scenes by human operators or computer vision systems [11], etc.

Actually, speckle filtering is a complex task in SAR image processing that has been approached in recent three decades by several researchers [12-15]. These pioneer works introduced by Lee [12, 13], Frost et al. [14] and Kuan et al. [15] have achieved single-look SAR image filtering which is, probably, the hardest case for denoising. Its complexity deals with the aforementioned nature and properties of the speckle as well as with the necessity to satisfy a set of contradictory requirements. It is desirable to suppress noise in homogeneous image regions, retain the mean values in these regions and simultaneously preserve valuable information as edges, small-size objects (targets) and texture features. It is often desirable to provide appropriately high visual quality of processed SAR images since visual inspection is still widely employed in solving such tasks as target detection and recognition, control point selection for data co-registration, etc.

Many researchers dealt with SAR despeckling method design and a lot of filters for SAR image denoising have been proposed in recent twenty years. There are several approaches worth mentioning. Locally adaptive speckle filters were designed in 90th of the previous century and the beginning of this century (see [16] and references therein). These techniques are based on hard or soft switching between two or several different filter outputs with paying special attention to local heterogeneity detection and detail preservation. Practically at the same time, wavelet based denoising techniques became popular [17-20]. A typical feature of wavelet based despeckling is that a three-stage procedure is commonly used where a logarithmic type direct homomorphic transform is applied to data at the first stage to yield an image corrupted by additive noise. Moreover, a problem with wavelet based filters is that it is quite difficult for them to carefully adapt to the spatial correlation of the speckle. Several techniques based on other than wavelet orthogonal transforms (e.g., DCT) [7, 21] have been proposed. These techniques are more effective in suppressing speckle in homogeneous image regions than the aforementioned Lee and Frost filters [12-14] and are able to easily adapt to multiplicative nature of the speckle and its spatial correlation. However, edge and detail preservation of the DCT based filters still requires improvements.

Other methods have been proposed in recent ten years as the improved sigma filter [22], anisotropic diffusion based approaches [23], non-local techniques [24, 25], methods based on heterogeneity detection [26], etc. All researchers focus on attaining a better trade-off between noise suppression in homogeneous image regions and fine detail preservation. The non-local methods are state-of-the-art in additive white Gaussian noise suppression nowadays [27, 28] and, being equipped by proper variance stabilizing transforms, they can process SAR images rather well [24]. However, the method performance depends upon how many similar patches are found and how large is this similarity between the found patches. Note that similar patches containing edges can be found with high enough probability and, thus, preserved well. Regarding small-size target preservation, this does not hold since there can be quite a small number of targets in a given SAR image and they can be not very similar to each other. For instance, the targets might have different contrasts with respect to background and various spatial shapes. These obstacles restrict target preservation ability of the approach [24].

In the sense of detail preservation, an interesting and powerful tool called Level Set method has been proposed recently [29-32]. Originally, the Level Set approach has been designed for image segmentation. An obvious advantage of this approach is that it is able to detect and localize heterogeneities in images reliably. This property can be used in SAR image filtering as well. There are impressive examples of real SAR image processing although the Level Set approach has not been intensively tested statistically and characterized quantitatively.

Thus, the main goal of this paper is to assess this approach for single-look SAR image processing and combine it with DCT and other orthogonal transform based filtering. The paper unfolds as follows. Section 2 briefly reviews and introduces the multiplicative model for speckle data analysis and the Level Set method used for object detection in noisy images. Additionally, it presents contrast and homogeneity measures and their relationships with speckle filtering and object detection. Section 3 reports the main results, namely, the performance analysis of the proposed approach for speckle filtering with small-sized object detection and preservation.

1. Object and heterogeneity detection: experiments with synthetic and real-life single-look SAR images

In this paper, we deal with single-look SAR images since they constitute the most complex and the most challenging case. Typically, the first studies and tests on SAR data have been performed for synthetic images assuming the following typical model of noisy image:

$$I_{ij}^{n} = I_{ij}^{true}\mu_{ij}, \quad (1)$$

where I_{ij}^{true} denotes the true image value for the ij-th pixel and μ_{ij} is multiplicative noise with unity mean, variance $\sigma_\mu^2 = 0.273$ and Rayleigh probability density function (pdf) assumed spatially uncorrelated (i.i.d.).

In this paper, we employ a Level Set method for object detection that also provides contour extraction. This method is based on the Hamilton-Jacobi equation [33], and furthermore several works have testified its efficiency for SAR image segmentation [29, 30, 34]. The Level Set-based method is an active contour technique whose front movement is driven by

$$\psi^{(k+1)} = \psi^{(k)} - \Delta t \psi_t \left|\nabla \psi^{(k)}\right|. \quad (2)$$

The term $\psi^{(k)}$ is the level set surface in *k*-th iteration where $\psi^{(0)}$ is an initial surface (usually $\psi^{(0)} \in [-1;1]$), Δt is the step time and $|\nabla(\cdot)|$ is the gradient magnitude of the initial surface. The term ψ_t is the evolution (or velocity) function which defines the front movement. In this work, we have adopted the Level Set evolution law proposed in [29] to detect punctual targets. The propagation function is based on the locally estimated variation coefficient (CV) and a homogeneity threshold introduced in [35] as

$$T = 1 + \frac{\sqrt{1+2\sigma_\mu^2}}{\sqrt{2M^2}}\sigma_\mu, \quad (3)$$

where M is the window size and σ_μ is the theoretical standard deviation of speckle. The target detection model is [29]:

$$\psi_t = (\hat{\sigma}_\mu - T) - \varepsilon\kappa \,. \qquad (4)$$

The term $\varepsilon\kappa$ is the curvature velocity described in [33] and $\hat{\sigma}_\mu$ stands for the local estimate of σ_μ. The final segmentation results are given by zero crossing points of $\psi^{(k)}$.

Fig. 1 displays some results of applying this method to a simulated SAR image. This image models large homogeneous regions of different mean, one large textural region, few prolonged objects (as fences in natural images). Besides, we have specially added fifteen small sized objects into homogeneous regions of different mean intensity.

Not surprisingly, three objects that present the largest contrast with respect to surrounding background have been detected (see the upper central part of the image). Other small sized objects have not been detected, and they cannot be detected visually since they present less contrast. Surprisingly, the large textural area has been detected. Hence, the Level Set method can be useful in SAR image processing.

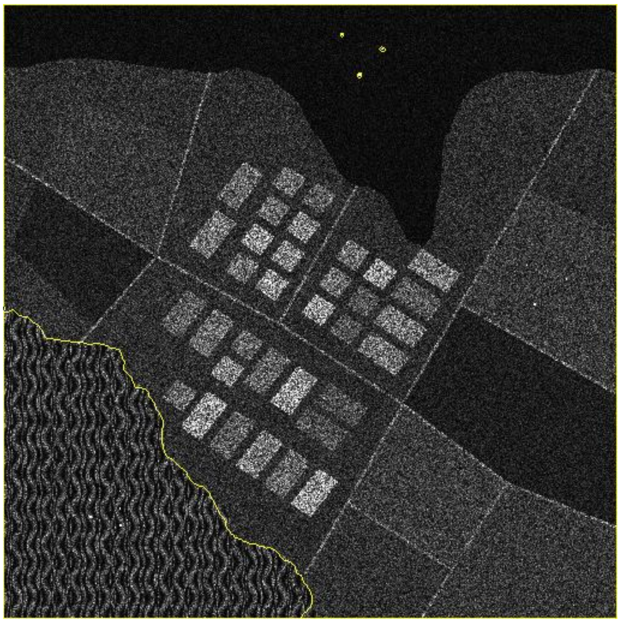
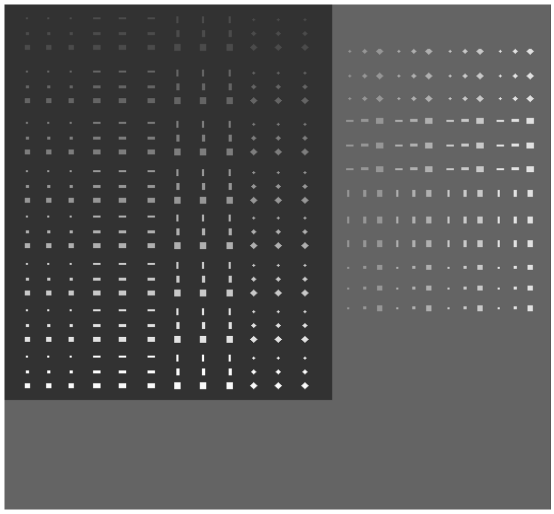


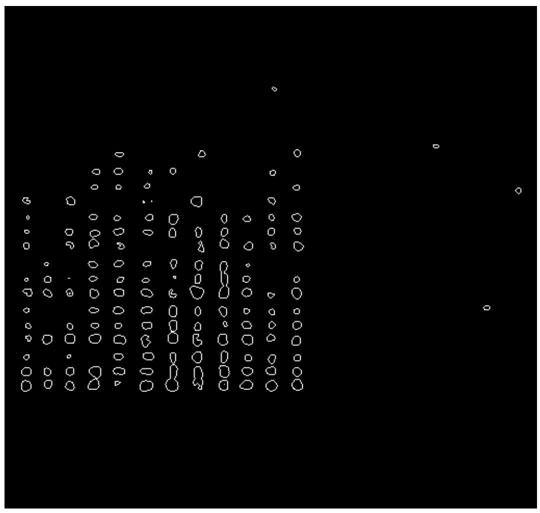
Fig. 1. Noisy test image with fifteen small-sized objects and detection results

These results of preliminary analysis show that, similarly to other detection techniques, the performance of the Level Set method depends upon object contrast. Here by contrast we assume the ratio $C=I_{obj}/I_{bg}$ where I_{obj} is the true image value assumed the same for all pixels that belong to a small object and I_{bg} denotes the true value for the surrounding background. Our experiments have demonstrated that for C=1.6 the Level Set approach does not detect objects, mainly because of the intensive speckle influence. Thus, it is reasonable to study the influence of the object contrast on the object detectability. Moreover, it is possible to expect that the probability to correctly detect an object P_{cd} depends upon a number of pixels that belong to it.

Tests with another noisy image have been carried on to assess the algorithm performance. Fig. 2(a) illustrates a specially created noise-free image with a quite large number of small-sized objects used to test the Level Set based object detection. The objects present different contrasts with respect to homogeneous background and *C* varies from 1.5 to 5.0. The objects have different number of pixels N_{sso}. The i.i.d. speckle has been modeled for the image in Fig. 2(a) and, furthermore, our detection method has been applied to it. Fig. 2(b) displays the object detection results.



a



b

Fig. 2. Synthetic image: a - the noise-free test image, b - object detection over the speckled image version

The visual analysis of the map shows that an object is detected with higher probability, when its contrast or the parameter N_{sso} are not small (e.g., $N_{sso} > 9$).

Table 1

Probability of correct detection for different object contrasts

Object Contrast	Probability of Correct Detection
1.50	0.000
2.00	0.014
2.25	0.028
2.50	0.070
3.00	0.380
3.50	0.760
4.00	0.850
4.50	0.920
5.00	0.950

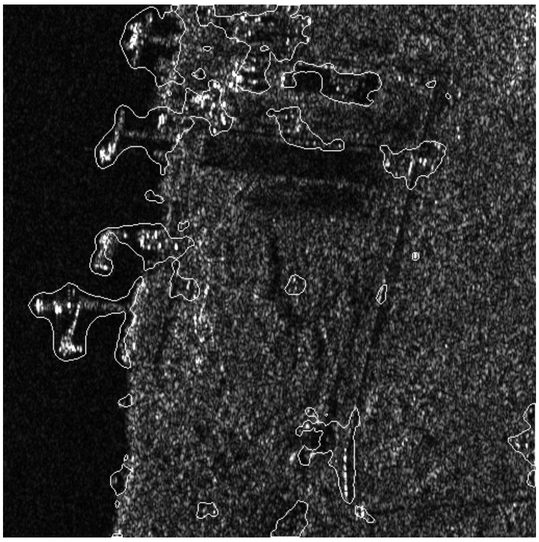
Another important issue is that objects with a larger N_{sso} are detected quite satisfactorily. Although we do not present statistical results to confirm this statement, tests with Fig. 2(a) and 2(b) illustrate this tendency, clearly.

One more advantage of the Level Set approach is that no false detections have been observed for the simulated image, although small-sized objects with low *C* have been missed. Usually, it is a hard task to achieve appropriate trade-off between probability of correct detection and false alarm rate by setting a proper threshold in target detection algorithms [1]. The Level Set method attains this task quite well without producing falsely detected targets, and it also provides correct detection for objects with rather low contrasts with respect to the surrounding background.

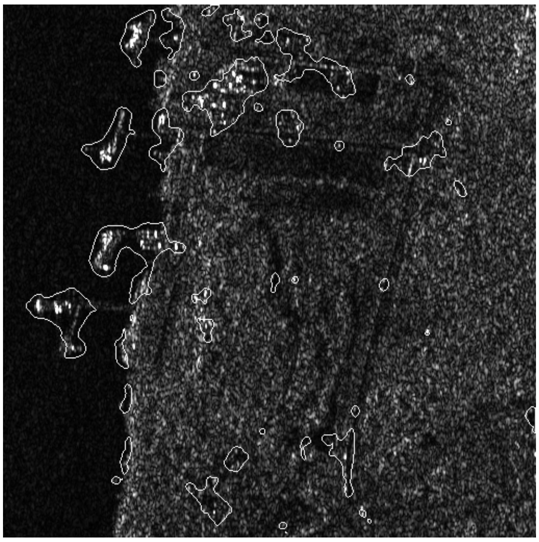
Concerning experiments with real-life SAR images, we have tested the algorithm on TerraSAR-X images. There are several single-look images presented in complex-valued form at http://www.infoterra.de/tsx/freedata/start.php. Thus, we have formed amplitude single-look images of size 512x512 pixels for a region in Indonesia for HH and VV polarization data as Fig. 3 illustrates it. These images are characterized by rather high cross-correlation (similarity). The cross-correlation factor for original (noisy) images is equal to 0.63. If the images are processed by an effective speckle filter, the cross-correlation factor increases and becomes about 0.8 [36]. When applied to these SAR images, the Level Set method produces contours around small-sized objects or other heterogeneities. Figs. 3(a) and 3(b) show these contours in white color. The results for the two considered images are quite similar.

2. Combined approaches to despeckling

Methods for image denoising based on orthogonal transforms have been briefly discussed in Introduction. The ones based on DCT presents several advantages regarding SAR image despeckling [7]. The standard DCT filter developed for speckled image processing performs as follows [7]. The DCT transform is applied to each image block (that usually has the size of 8x8 pixels) and hard thresholding is applied to the resulting DCT coefficients.



a



b

Fig. 3. HH (a) and VV (b) polarization single-look TerraSAR-X images of the region in Indonesia with heterogeneous areas detected by the Level Set method

The thresholds are set adaptively and individually for each block as $T(m,n) = \beta\sigma_{\mu} I_{mn}^{mean}$ where β is a constant factor, σ_{μ} is the standard deviation of the multiplicative noise (equal to 0.52 for single-look amplitude SAR images). I_{mn}^{mean} stands here for the local mean for a given image block, m and n define the block leftmost upper corner indices. The standard recommendation is to set β equal to 2.6.

After the thresholding operation, the inverse DCT is performed. The filtered values, in opposite to scanning window filtering, are obtained for all pixels that belong to a given block. At the final stage, for each pixel the obtained filtered values that come from different blocks are averaged if filtering with block overlapping is applied. Note that DCT and, in general, other block-wise orthogonal transform based filtering can be carried out with non-overlapping, partly overlapping and fully overlapping blocks. In the latter case, processing provides the most efficient despeckling [7], although more computation is required. Since the main task in SAR image despeckling is to suppress noise efficiently, filtering with full overlapping of blocks is considered in the following.

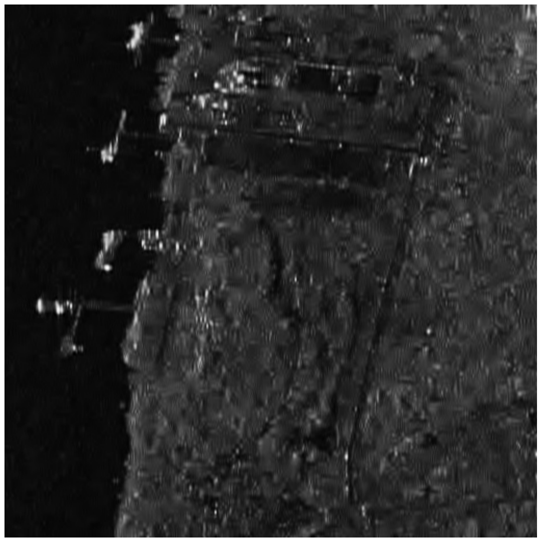
Variants of the DCT based filtering other than described above are possible to devise. First of all, if speckle is spatially correlated as this happens in practice, it is reasonable to use hard frequency dependent thresholds: $T(m,n,k,l) = \beta\sigma_{\mu} I_{mn}^{mean} \sqrt{W_{kl}}$ where W_{kl} is the normalized DCT spectrum of the speckle, *k* and *l* are indices in the DCT domain. The use of frequency dependent thresholding produces considerable filtering efficiency improvement compared to the standard DCT based filter, for homogeneous and textural image regions [9, 21, 37]. However, the small-size object preservation is worth improving. Besides, specific artifacts might be observed in homogeneous regions. They occur due to hard thresholding which is a strict rule. The aforementioned effects can be seen in output images obtained for hard thresholding and frequency dependent thresholds (see images in Fig. 4). Similar effects are observed for another TerraSAR-X image of Uluru region (see Fig. 5).

The performance of the DCT based filter can be improved in several ways. For example, it is possible to apply the so-called combined threshold instead of hard one to reduce artifacts in output images [38]. For this purpose, the DCT coefficient thresholded value is calculated as

$$D_t(m,n,k,l) = \\ = \begin{cases} D(m,n,k,l), \\ \quad \text{if} |D(m,n,k,l)| \ge \beta\sigma_{\mu} I_{mn}^{mean} \sqrt{W_{kl}}; \\ D^3(m,n,k,l) / (\beta\sigma_{\mu} I_{mn}^{mean} \sqrt{W_{kl}})^2 \\ \quad \text{otherwise.} \end{cases} \quad (5)$$

The recommended value of β in this case is about 4. The output images contain less artifacts in homogeneous and textural regions. Two examples are presented in Fig. 6 for HH and VV original images depicted in Fig. 3. However, detail preservation is still worth improving since small sized objects are smeared.

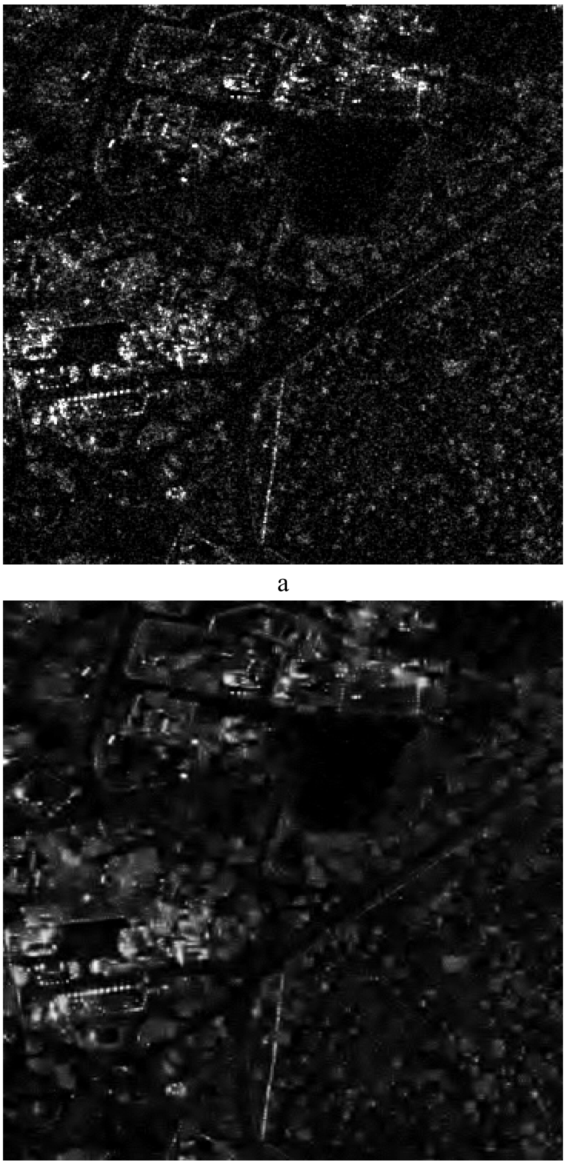
a



b

Fig. 4. HH (a) and VV (b) polarization single look TerraSAR-X images after processing by the DCT-based filter with hard frequency dependent thresholding

A general property in the DCT based filtering is that setting the threshold slightly smaller than recommended leads to less efficient noise suppression but better visual quality due to more careful preservation of edges and details [37, 38]. Note that smaller threshold can be provided in several ways. The first possible way is to set β smaller than recommended above. The second way it to use a block median value I_{mn}^{med} instead of I_{mn}^{mean} as equation (5) states. Note that $I_{mn}^{med} < I_{mn}^{mean}$ in image homogeneous regions for Rayleigh pdf of speckle. And $I_{mn}^{med} < I_{mn}^{mean}$ for blocks that contain small-sized targets with positive contrast (usually the small-sized objects of interest have just positive contrast with respect to surrounding background).

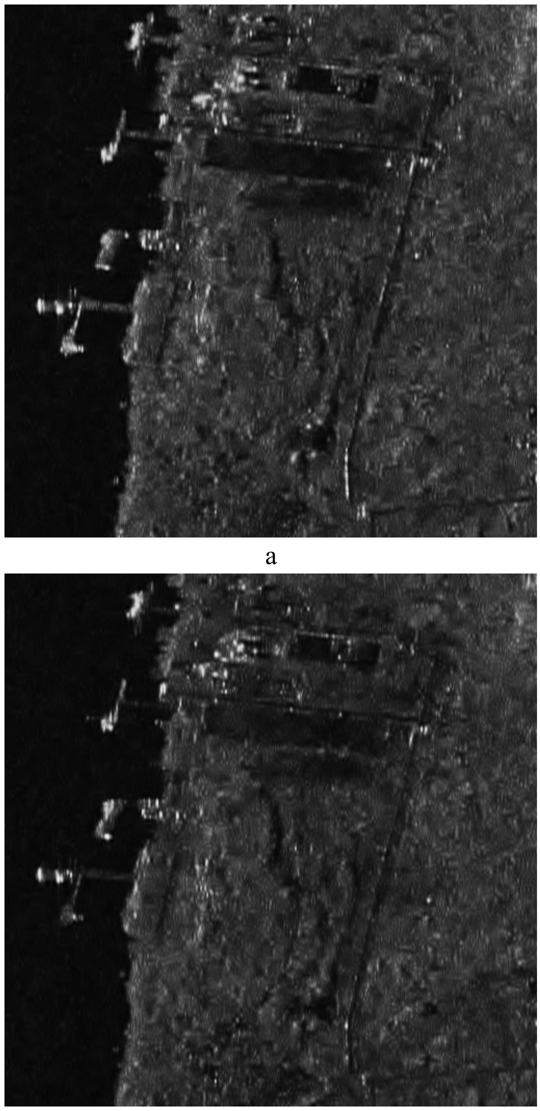


a

b

Fig. 5. Original HH SAR image (a) and output image for the DCT-based filter with hard frequency dependent thresholding (b)

Moreover, better detail preservation can be achieved in several other ways. For example, one can apply the standard DCT filter with frequency independent threshold calculated as $T(m,n)=\beta\sigma_{\mu}I_{mn}^{mean}$ or $T(m,n)=\beta\sigma_{\mu}I_{mn}^{med}$. Besides, it is possible to apply another orthogonal transform (e.g., Haar wavelet in blocks of 8x8 pixels) which is better suited for preserving sharp transitions in images than DCT). The thresholds are then set as $T(m,n)=\beta\sigma_{\mu}I_{mn}^{mean}$ or $T(m,n)=\beta\sigma_{\mu}I_{mn}^{med}$ where the recommended β for the Haar wavelet is equal to 3.5.



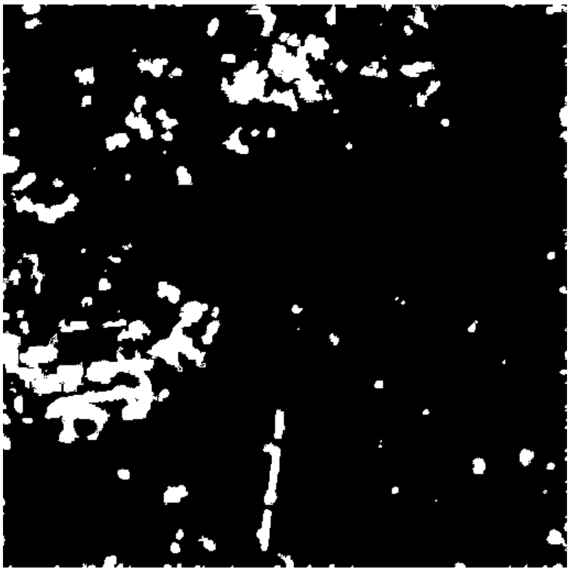
a

b

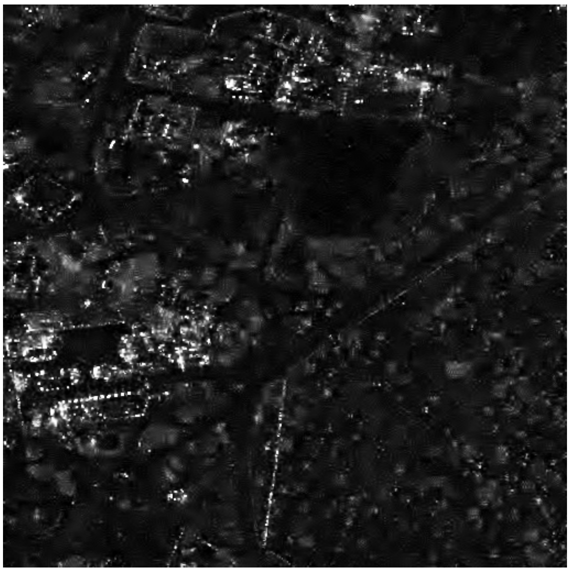
Fig. 6. HH (a) and VV (b) polarization single-look TerraSAR-X images after processing by the DCT-based filter with combined frequency dependent thresholding (5)

Our task here is to demonstrate that the use of such approaches can be suitable. Note that the use of aforementioned “detail-preserving” filtering is reasonable only for edge/detail neighborhoods. Thus, we apply the Level Set method for detecting such neighborhoods.

Note that the Level Set method outcomes can be presented as a binary map. For example, for the image in Fig. 5(a) the obtained binary map is shown in Fig. 7(a), where white pixels indicate the detected detail neighborhoods. The algorithm proceeds by considering that a block belongs to such a neighborhood, if more than a half of its pixels have unities in the corresponding binary map. Then, a detail preserving denoising is carried out for this block. Otherwise, a conventional filtering with frequency dependent threshold is carried out. Fig. 7(b) displays an example of the proposed filtering processing for the image in Fig. 5(a). The locally adaptive combination DCT/Haar has been applied and furthermore a visual comparison of this output image (Fig. 7(b)) and one in Fig. 6(b) clearly shows that the small-sized objects are better preserved.



a

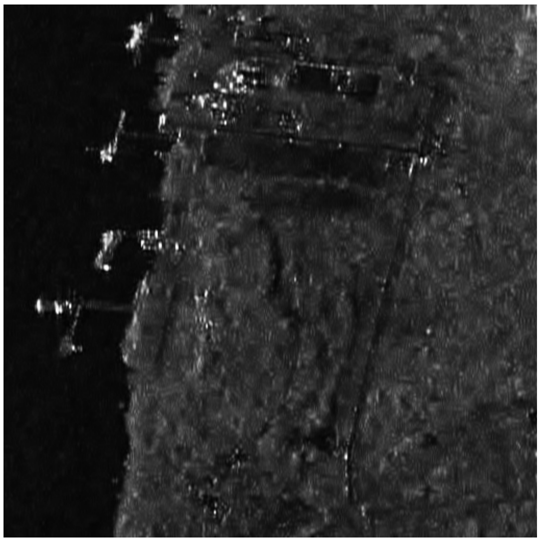


b

Fig. 7. The edge map obtained by the Level Set method (a) and the output of the proposed locally adaptive transformed based filter (b)

Let us analyze the results for another version of the locally adaptive method. The DCT-based filter with combined frequency dependent thresholding ($\beta = 4.5$) is applied to homogeneous image regions whilst the standard DCT-based filter with $T(m,n) = \beta\sigma_{\mu} I_{mn}^{med}$ is applied to the detected heterogeneous regions ($\beta = 2.6$). The outputs are presented in Fig. 8. The comparison of these images with the corresponding output ones in Fig. 6 shows that the small sized objects are preserved considerably better. In other regions, there are no differences since the same filtering algorithm is applied.

a



b

Fig. 8. HH (a) and VV (b) polarization single look TerraSAR-X images after processing by the DCT-based filter with combined frequency dependent thresholding (5) and taking into account heterogeneities detected by the Level Set method

Noise-free images are not available for performance assessment of the filtering methods in our case. Thus, it is only possible to compare speckle suppression efficiency in homogeneous image regions as, e.g., water surface in the left part of the images in Figs. 4, 6, and 8. The estimated residual variances of speckle $\sigma^2_{\mu\,res}$ are about 0.027, 0.035, and 0.029 for the images in Fig. 4, 6, and 8, respectively. Thus, the combined thresholding produces slightly worse results than hard thresholding. Anyway, speckle intensity is reduced by approximately 10 times for the considered DCT-based despeckling methods (the estimated σ^2_{μ} for the selected fragment is about 0.28). In fact, the efficiency of noise suppression can be improved for larger β values.

For comparison purposes, consider speckle suppression in homogeneous region for other filters. If the standard DCT-based filter with hard frequency-independent thresholding is applied (with $\beta = 2.6$), $\sigma^2_{\mu\,res}$ is about 0.114, i.e., essentially larger. These results clearly demonstrate expedience of using frequency dependent thresholding in DCT-based filtering. The local statistic Lee filter with 7x7 scanning window produces $\sigma^2_{\mu\,res}$ about 0.045, i.e. essentially larger than for the DCT- based filter with hard or combined frequency-dependent thresholding. Moreover, detail preservation for the Lee filter output image is worse than for the images in Fig. 8.

Conclusions

In this paper, we have demonstrated that suppression of spatially correlated speckle is not an easy task especially when it is associated with detail preservation. In order to overcome this shortcoming, we have applied a Level Set-based method to detect heterogeneities in SAR images and furthermore indicate image fragments for which detail preservation is the first order task. Then, the DCT based filter with frequency-dependent threshold provides efficient speckle suppression in image regions recognized as homogeneous. Several approaches for better detail preservation were put forward and tested for real-life single-look SAR images. Our future studies will be focused on quantitative assessment of the proposed filters for simulated single-look images with speckle properties similar to those observed in practice.

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СОВМЕСТНОЕ ИСПОЛЬЗОВАНИЕ МЕТОДА УРОВНЕВЫХ МНОЖЕСТВ И ОРТОГОНАЛЬНЫХ ПРЕОБРАЗОВАНИЙ ДЛЯ ПОДАВЛЕНИЯ СПЕКЛА НА РСА-ИЗОБРАЖЕНИЯ

Д.В. Февралев, С.С. Кривенко, В.В. Лукин, Р. Маркес, Ф. де Медейрос

Эта статья описывает новый подход для фильтрации изображений радиолокаторов с синтезированной апертурой (РСА). Она сочетает в себе метод установки порога для неоднородных участков и дискретно-косинусное преобразование или преобразование Хаара для подавления спекла и сохранения малоразмерных объектов. Испытания были проведены на одном синтетическом и нескольких реальных данных РСА. Кроме этого, представлены некоторые результаты по оценке алгоритма в соответствии с качественными и количественными критериями. Исследования с синтезированными и реальными радиолокационными изображениями показали, что предлагаемый подход эффективен в фильтрации спекла и сохраняет малогабаритные объекты и текстуры.

Ключевые слова: одновзглядовые изображения РСА, фильтрация спекла, метод уровневых множеств, ДКП, обнаружение целей.

СПІЛЬНЕ ВИКОРИСТАННЯ МЕТОДУ РІВНЕВИХ МНОЖИН І ОРТОГОНАЛЬНИХ ПЕРЕТВОРЕНЬ ДЛЯ ПРИДУШЕННЯ СПЕКЛУ НА РСА-ЗОБРАЖЕННЯХ

Д.В. Февральов, С.С. Кривенко, В.В. Лукін, Р. Маркес, Ф. де Медейрос

Ця стаття описує новий підхід для фільтрації зображень радіолокаторів із синтезованою апертурою (РСА). Вона поєднує в собі метод установки порога для неоднорідних ділянок і дискретно-косинусне перетворення або перетворення Хаара для придушення спеклу і збереження малорозмірних об'єктів. Випробування були проведені на одному синтетичному та кількох реальних даних РСА. Крім цього, представлено деякі результати по оцінці алгоритму у відповідності із якісними та кількісними критеріями. Дослідження з синтезованими і реальними радіолокаційними зображеннями показали, що запропонований підхід ефективний у фільтрації спекла і зберігає малогабаритні об'єкти і текстури.

Ключові слова: однопоглядове зображення РСА, фільтрація спекла, метод рівневих множин, ДКП, виявлення цілей.

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