The object of this study is the process of filtering images acquired from a space radar observation system. The task to filter images from a space radar observation system has been solved by applying the Kuan algorithm.

The results reported here include the following:

– the defined basic stages of the method for filtering images acquired from a space radar observation system based on the Kuan algorithm;

– the performed experimental study on filtering images from a space radar observation system based on the Kuan algorithm.

A method for filtering images from a space radar observation system based on the Kuan algorithm has been improved. Special features of the improved method, in contrast to those in established ones, are:

– selection of a local filtering window;

– calculation of local statistical characteristics;

– calculation of variation coefficients;

– calculation of the Kuan weight coefficient;

– sequential filtering of image pixels using the "sliding" window method.

A visual analysis of radar image filtering by an improved method based on the Kuan algorithm and known methods based on the Li algorithm and Frost algorithm were carried out. The use of the improved method when filtering an image acquired from a space radar surveillance system made it possible to increase the signal-to-noise ratio. That became possible due to the use of the Kuan algorithm. The choice of the Kuan algorithm has made it possible to achieve a 21% gain in the maximum signal-to-noise ratio in comparison with the known method (based on the Li algorithm).

The scope of the improved method application includes filtering images from space radar surveillance systems. Conditions for practical implementation of the results are specialized software in software-hardware systems for processing radar images

Keywords: space radar surveillance system, image filtering, Kuan algorithm, signal-to-noise ratio

IMPROVING A METHOD FOR FILTERING IMAGES ACQUIRED FROM A SPACE-BASED RADAR OBSERVATION SYSTEM BASED ON THE KUAN ALGORITHM

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1. Introduction

Images acquired from space-based radar surveillance systems are used to solve diverse tasks in various fields [1, 2]. These include, for example, environmental monitoring, agriculture, water surface monitoring, defense and security, etc. [3].

A feature of images from space-based radar surveillance systems is the presence of certain artifacts [4, 5]. Such arti-

facts are caused by the existence of speckle noise, which, in turn, leads to image graininess [6]. A feature of speckle noise is its multiplicative nature, which leads to image quality degradation [5, 6]. Therefore, the process of filtering images from space-based radar surveillance systems is an important stage of image processing.

Known image filtering methods, for example, [7, 8], have certain advantages for images acquired from space-based optoelectronic surveillance systems. The use of known methods for filtering images from space-based radar surveillance systems leads to a deterioration in the quality of such images. The main disadvantages of known methods of filtering images from space radar observation systems are primarily related to the failure to take into account the multiplicative nature of speckle noise.

Therefore, solving the task of improving a method for filtering images acquired from space radar observation systems is a relevant scientific issue.

2. Literature review and problem statement

Methods for global threshold processing of images acquired from radar surveillance systems were proposed in [9]. The main advantage of methods [4] is the simplicity of implementation. However, the quality of the processed image remained unresolved. The reason for this is an artifact in the form of speckle noise. An option to overcome this is not to use a global threshold. This is the approach used in [10].

In it, the use of the method for local threshold processing of images from space radar surveillance systems was proposed. The main advantages of [10] are the use of a local processing window with the same threshold level within this window. However, the issues of speckle noise filtering remained unresolved. The reason is the failure to take into account heterogeneous processing artifacts. An option to overcome this is the texture processing method. This is the approach considered in [11].

In it, a texture method for processing radar images was proposed. The advantages of [11] are the use of the method for processing radar images of different scales. But the issue of isolating objects of interest under the influence of speckle noise remains unresolved. An option to overcome this is to use clustering methods. This is the approach used in [12].

In it, a k-means clustering method for radar images is proposed. The advantage of [12] is invariance to a priori information and simplicity of implementation. The main disadvantage is the dependence on the input data set for training and the need to conduct the training itself.

In [13], a modified clustering method is proposed. The advantage is to obtain acceptable results in the presence of artifacts in radar images. The disadvantages are significant computational costs.

In [14], a comprehensive method was proposed to reduce speckle noise in images acquired from space-based radar observation systems. The method combines an extended adaptive Wiener filter at the first stage and an extended controlled filter at the second. The main advantage is good performance in suppressing the speckle noise effect while simultaneously preserving contours and small details in the radar image. The main disadvantage is the high computational cost and the dependence of the quality of the result of the method on the choice of filtering parameters.

In [15], a method based on adaptive selection of the size of the Lie filter window was proposed for processing radar images obtained from the Sentinel-1 spacecraft. The method is based on the analysis of local statistical characteristics of the original radar image and the assessment of the effectiveness of reducing the speckle noise effect. Based on the results of such actions, the optimal size of the Li filter window for individual sections of the radar image is automatically determined. The main advantages are the preservation of contour details and texture in the radar image and the reduction of the effect of speckle noise without significant loss of spatial resolution of the image. At the same time, the main disadvantages are the dependence of the quality of the processing result on the accuracy of the assessment of local statistical characteristics. This, in turn, leads to an increase in computational costs.

In [16], a genetic algorithm for image processing is proposed. The advantage of this method is ensuring the visual quality of the original image. The main disadvantage is the failure to take into account the presence of speckle noise in the image. An option to overcome this is to highlight special information zones in the image. This is the approach proposed in [17].

In it, a method for selecting special information areas in an image is proposed. The advantage of [17] is the reduction of image processing time. The disadvantage is the failure to take into account the presence of speckle noise in the image.

In [18], it is proposed to use an adaptive sigma-point Kalman filter with importance sampling. The method involves taking into account the statistical characteristics of speckle noise and adaptively adjusting the filter parameters. The main advantage is to increase spatial resolution and reduce the impact of speckle noise. The main disadvantage is the complexity of implementing the filter under conditions of processing large data sets (large volume of radar images).

In [19], a filtering method is proposed to reduce speckle noise in radar images from the Sentinel-1 spacecraft. The method is based on the selection of Frost filter parameters based on the prediction of the descaling efficiency. Descaling is the process of reducing and/or removing speckle noise in radar images. The method evaluates the local statistical characteristics of the radar image. Subsequently, based on the obtained estimates, the descaling efficiency indicators are predicted. At the next stage, the optimal values of the Frost filter parameters are automatically selected. The advantage of [19] is the preservation of texture and contour details in radar images while simultaneously reducing speckle noise. The disadvantage is the complexity of the algorithm due to its multi-stage nature.

In [20], a method based on the ant colony algorithm is proposed. The proposed method involves adaptive adjustment of the input parameters of the ant colony algorithm in order to improve the quality of the selection of objects of interest in the original images. The main advantage is the ability to select objects of interest in images with speckle noise with high segmentation quality indicators. The main disadvantage is that the results of the method are represented only on optoelectronic images. This calls into question its versatility, namely the possibility of using it for processing radar images acquired from space radar observation systems.

Thus, our review of known methods for filtering images from space radar observation systems indicates the presence of certain disadvantages:

– high computational complexity;

– low signal-to-noise ratio;

– partial consideration of the effect of speckle/noise on the radar image;

– difficulty of implementation under conditions of large volumes of radar images.

The above indicates the feasibility of research aimed at improving a method of filtering images acquired from a space radar surveillance system.

3. The aim and objectives of the study

The aim of our research is to increase the signal-to-noise ratio when filtering images acquired from a space-based radar surveillance system using the Kuan algorithm. The Kuan algorithm was chosen based on the features of its application for filtering heterogeneous images (medical, natural landscapes, in the interests of agriculture, etc.) under conditions of speckle noise (for example, [21, 22]). The use of the Kuan algorithm will make it possible to improve the quality of radar image processing.

To achieve the goal, the following tasks were set:

– to define the main stages of the method for filtering images from a space-based radar surveillance system based on the Kuan algorithm;

– to conduct an experimental study on filtering images from a space-based radar surveillance system based on the Kuan algorithm.

4. The study materials and methods

The object of our study is the process of filtering images acquired from a space radar surveillance system.

The principal hypothesis assumes that improving a method for filtering images from a space radar surveillance system based on the Kuan algorithm could make it possible to increase the signal-to-noise ratio.

The following assumptions were adopted in the study:

– the radar image from the space surveillance system was taken as the source;

– the radar image has (0–255) grayscale levels.

The following simplifications were accepted for the study:

– speckle noise was considered as an artifact;

– speckle noise is simulated with specified statistical characteristics;

– other types of artifacts in the image were not considered.

The experimental study employed the following:

– hardware: DELL Intel(R) Core(TM) i7-8650U CPU @ 1.90GHz (2.11 GHz) (USA) laptop;

– software: object-oriented programming language Python 3.12 (The Netherlands).

The following general methods were used in the research:

– digital image processing;

– digital signal processing;

– mathematical apparatus of matrix theory;

– probability theory and mathematical statistics;

– spectral analysis;

– empirical research;

– mathematical modeling;

– comparative research.

Our research methods were selected taking into account the tasks formulated in chapter 3.

When defining the main stages of the method for filtering images acquired from a space radar observation system based on the Kuan algorithm, the following theoretical methods were used:

– digital signal processing;

– digital image processing;

– mathematical apparatus of matrix theory;

– probability theory and mathematical statistics;

– spectral analysis.

When conducting an experimental study on filtering images from a space radar observation system based on the Kuan algorithm, the following theoretical and practical research methods were used:

– digital image processing;

– empirical research;

– mathematical modeling;

– comparative research.

5. Results of investigating the method of filtering images acquired from a space radar surveillance system

5. 1. Main stages of the method for filtering images from a space radar surveillance system

The main stages of the method for filtering images from a space radar surveillance system based on the Kuan algorithm are shown in Fig. 1.
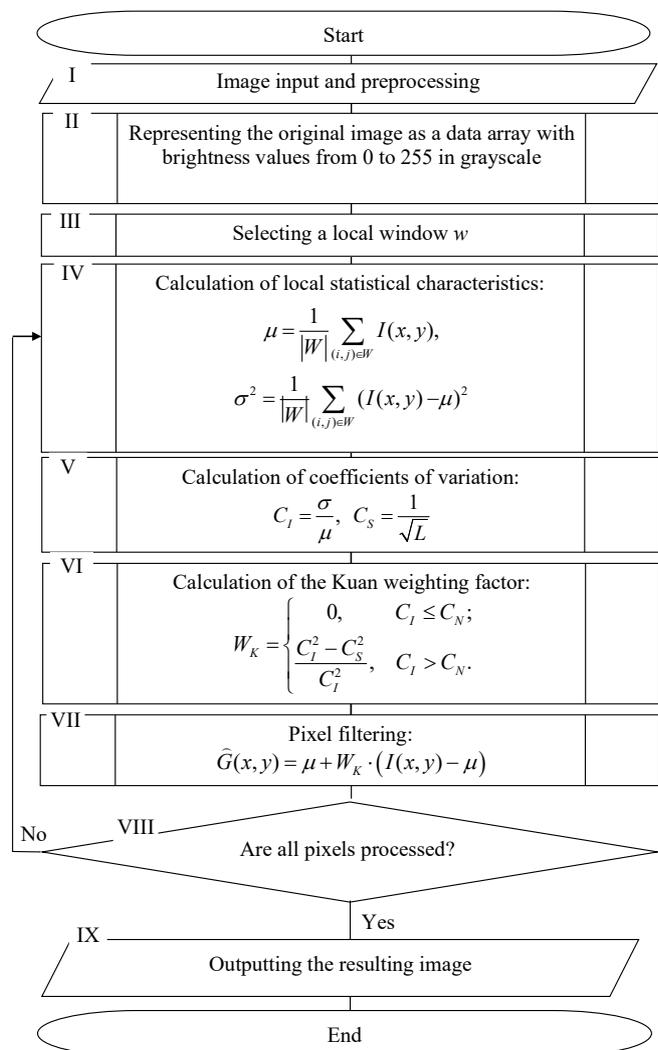

Fig. 1. Main stages of the method for filtering images acquired from a space radar surveillance system based on the Kuan algorithm

The main stages of the method for filtering an image from a space radar observation system based on the Kuan algorithm are:

1) input of the source image from a space radar observation system;

2) representation of the source image as a data array with brightness values from 0 to 255 in grayscale;

3) selection of a local window for further filtering. For further filtering of the radar image, a local window w is set for each pixel of the image;

4) calculation of local statistical characteristics. At this stage, within the boundaries of the selected local window, such local statistical characteristics as the mathematical expectation and variance are calculated.

The mathematical expectation μ and variance σ^2 for each pixel of the image with the row and column indices of its location (coordinates) (i, j) are calculated within the selected local processing window w according to expressions (1) and (2), respectively:

$$\mu = \frac{1}{|W|} \sum_{(i,j) \in W} I(x,y), \tag{1}$$

$$\sigma^2 = \frac{1}{|W|} \sum_{(i,j) \in W} \left(I(x,y) - \mu \right)^2, \tag{2}$$

where $|W|$ is the total number of pixels in the selected local window w;

5) calculation of variance coefficients. At this stage, for further differentiation of homogeneous and heterogeneous areas in the image, the local variance coefficient C_I and the theoretical variance coefficient of speckle noise C_S are calculated using expressions (3) and (4), respectively:

$$C_I = \frac{\sigma}{\mu}, \tag{3}$$

$$C_S = \frac{1}{\sqrt{L}}, \tag{4}$$

where L is the number of pulses used to form a pixel of the output image from the space radar observation system;

6) calculation of the Kuan weighting factor. At this stage, based on the calculated coefficients of variation, the Kuan weighting factor w_k is calculated, which determines the degree of smoothing, according to expression (5):

$$W_K = \begin{cases} 0, & C_I \le C_N; \\ \dfrac{C_I^2 - C_S^2}{C_I^2}, & C_I > C_N. \end{cases} \tag{5}$$

That is, in homogeneous areas, stronger smoothing will occur, and in heterogeneous areas, details and boundaries will be preserved;

7) pixel filtering. At this stage, the "filtered" value of each pixel of the image is determined from expression (6)

$$\hat{G}(x,y) = \mu + W_K \cdot \left(I(x,y) - \mu \right), \tag{6}$$

where $\hat{G}(x,y)$ – "filtered" value (x,y);

8) sequential processing of pixels of the entire image

To process pixels of the entire image, it is necessary to proceed to stage 4. And for each pixel of the image, we per-

form calculations according to expressions (1)–(6). Therefore, this approach allows us to evenly reduce the effect of speckle noise on the entire image and adapt the processing to the local features of the shooting surface;

9) output of the resulting (filtered) image.

Thus, the method for filtering an image acquired from a space radar observation system based on the Kuan algorithm has been improved, in which, unlike the known ones,

– a local filtering window is selected;

– local statistical characteristics are calculated (mathematical expectation and variance);

– variance coefficients are calculated;

– Kuan weight coefficient is calculated;

– sequential filtering of image pixels is performed using the "sliding" window method.

5. 2. Experimental study on filtering an image from a space radar surveillance system

To conduct an experimental study on filtering an image acquired from a space radar surveillance system based on the Kuan algorithm, an image (Fig. 2 [23]) was selected as the initial image.

Fig. 2. Original image from a space-based radar surveillance system [23]

This image was acquired from the Sentinel-1 space-based radar observation system (European Space Agency) [23]. The original image (Fig. 2) was downloaded from the website (https://surl.li/kjfphq) of the European Earth observation program Sentinel [23]. The Sentinel program provides free and open data (images) from space-based radar observation systems for scientific and applied purposes [23].

Subsequently, speckle noise was added to the original image. It was taken into account that speckle noise, which is characteristic of radar images, has a multiplicative origin model. That is, the value of each pixel of the original image from the space-based radar observation system (Fig. 2) can be represented in the following form (7)

$$I(x, y) = G(x, y) \cdot S(x.y), \tag{7}$$

where $I(x, y)$ is the pixel value of the original radar image;

$G(x, y)$ is the value of the true signal, i.e., the signal reflected from the ground surface;

$S(x.y)$ is the speckle noise value.

Fig. 3 shows the original image (Fig. 2), which is distorted by speckle noise according to expression (7). The root mean square deviation of the speckle noise intensity $S(x.y)$ in Fig. 3 is equal to 1.

Fig. 4 shows a filtered image from a space-based radar surveillance system using the improved method based on the Kuan algorithm. The processing window size w is taken to be (15×15) pixels.

Analysis of Fig. 4 reveals an improvement in the visual quality of the distorted image (Fig. 3) when using the Kuan algorithm.

For comparative analysis, Fig. 5 shows a filtered image from a space radar observation system using the method based on the Lee algorithm [15]. The Lee algorithm was chosen for comparative analysis based on the fact that this algorithm is effective in comparison with other known filtering methods [15]. The processing window size w is taken to be (15×15) pixels.
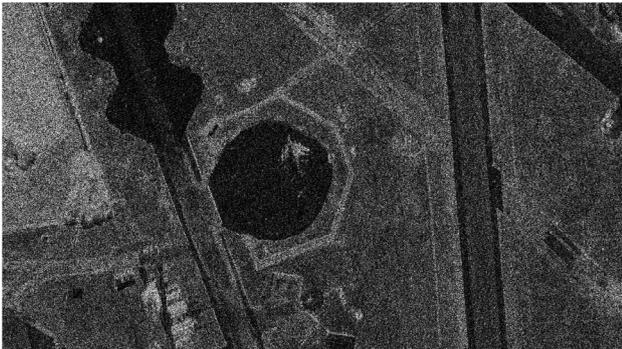

Fig. 3. The original image (Fig. 2) distorted by speckle noise according to expression (7)

Fig. 4. The filtered image from a space-based radar surveillance system using the improved method based on the Kuan algorithm
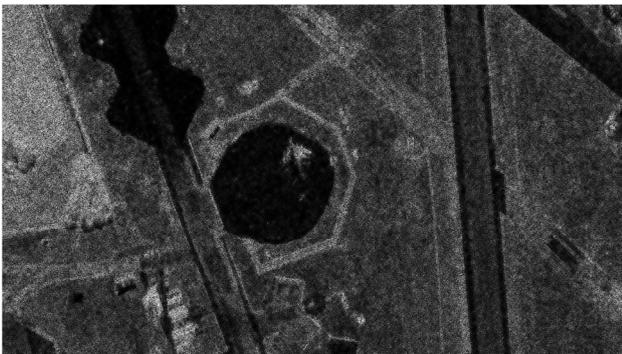

Fig. 5. The filtered image from a space-based radar surveillance system using a method based on the Lee algorithm

Additionally, for comparative analysis, Fig. 6 shows a filtered image from a space radar observation system using the Frost algorithm [19, 24]. The processing window size w is taken to be (15×15) pixels.
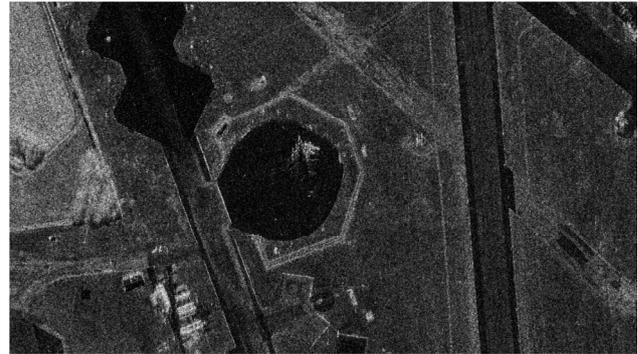

Fig. 6. The filtered image from a space-based radar surveillance system using a method based on the Frost algorithm

Comparative analysis of Fig. 4–6 reveals better visual quality of Fig. 4 compared to Fig. 5, 6.

For quantitative analysis, the signal-to-noise ratio was calculated for Fig. 4, 5. The calculation results are given in Table 1. At the same time, Table 1 shows the maximum value of the signal-to-noise ratio on the filtered images (Fig. 4, 5)

Table 1

Signal-to-noise ratio

Segmentation method ID	Processing window size w	Maximum signal-to-noise ratio
Improved filtering method based on Kuan's algorithm	(15×15)	23.33
Known filtering method based on Lee's algorithm	(15×15)	19.37
Known filtering method based on Frost's algorithm	(15×15)	15.76

Analysis of Table 1 reveals a gain in the maximum signal-to-noise ratio when using the improved method based on the Kuan algorithm in comparison with the known methods:
– by 21% (known method based on the Lee algorithm);
– by 48% (known method based on the Frost algorithm).

6. Discussion of results based on the improved method for filtering images acquired from a space radar observation system

The method of filtering images from a space radar observation system based on the Kuan algorithm has been improved, in which, unlike the known ones:
– a local filtering window is selected;
– local statistical characteristics are calculated (mathematical expectation and variance);
– variance coefficients are calculated;
– Kuan weight coefficient is calculated;
– sequential filtering of image pixels is performed using the "sliding" window method.

An experimental study on filtering images from a space radar observation system has been conducted. Fig. 3 shows the original image (Fig. 2), which is distorted by speckle noise according to expression (7). Fig. 4 depicts the filtered image

from a space radar observation system using the improved method based on the Kuan algorithm. The processing window size w is taken to be (15×15) pixels. Analysis of Fig. 4 reveals an improvement in the visual quality of the distorted image (Fig. 3) when using the Kuan algorithm.

For comparative analysis, Fig. 5 shows a filtered image from a space radar observation system using the method based on the Lee algorithm [15]. The processing window size w is taken to be (15×15) pixels.

Additionally, for comparative analysis, Fig. 6 shows a filtered image from a space radar observation system using the method based on the Frost algorithm [19, 24]. The processing window size w is taken to be (15×15) pixels.

Comparative analysis of Fig. 4–6 reveals a better visual quality of Fig. 4 compared to Fig. 5, 6.

For quantitative analysis, the signal-to-noise ratio was calculated for Fig. 4–6. The calculation results are given in Table 1. Analysis of Table 1 reveals a gain in the maximum signal-to-noise ratio when using the improved method based on the Kuan algorithm compared to the known methods:

– by 21% (known method based on the Lee algorithm);

– by 48% (known method based on the Frost algorithm).

This became possible thanks to the use of the Kuan algorithm for filtering images from a space radar surveillance system.

The improved method of filtering images from a space radar surveillance system based on the Kuan algorithm has made it possible to solve the problem part, namely:

– increase the maximum value of the signal-to-noise ratio by 21% compared to the known method (known method based on the Lee algorithm).

Limitations of our study:

– only the radar image from the space radar surveillance system was considered;

– only the effect of speckle noise was taken into account;

– rotation and scaling of the radar image were not taken into account.

The disadvantages of the study are:

– the complexity of implementing the improved method;

– the use of a fixed value of the processing window when applying the Kuan algorithm.

The development of this research may consist in optimizing the processing window size when using the Kuan algorithm.

7. Conclusions

1. The main stages of the improved method for filtering images acquired by from a space radar observation system based on the Kuan algorithm are:

– selection of a local filtering window;

– calculation of local statistical characteristics (mathematical expectation and variance);

– calculation of variance coefficients;

– calculation of the Kuan weight coefficient;

– sequential filtering of image pixels using the "sliding" window method.

2. An experimental study was conducted on filtering images from a space radar observation system. The choice of the Kuan algorithm has made it possible to provide a gain in the maximum signal-to-noise ratio by 21% compared to the known method (based on the Lee algorithm).

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Hennadii Khudov: Conceptualization, Methodology, Software, Investigation, Writing–review & editing, Supervision, Project administration; **Oleksandr Makoveichuk:** Validation, Data curation, Investigation, Software; **Serhii Tokarev:** Validation, Data curation, Writing-original draft, Visualization; **Artem Andriushchenko:** Data curation, Writing-original draft, Visualization; **Oleksandr Pukhovyi:** Resources, Writing-review & editing, Funding Acquisition; **Olexandr Rohulia:** Formal analysis, Data curation, Visualization; **Oleh Bilous:** Writing-review & editing, Supervision, Funding acquisition; **Mykola Verovok:** Formal analysis, Resources, Visualization; **Valeriy Samoylenko:** Formal analysis, Data curation, Resources, Visualization; **Vladyslav Khudov:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Visualization.

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