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RESEARCH ARTICLE

Stray Light Suppression of Wide-Field Surveillance in Complicated Situations

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ABSTRACT Wide field and long exposure time can effectively improve the ability of space surveillance telescope to detect weak space targets. However, this is easily affected by stray light, resulting in the effective target submerged in the background of stray light. Based on the basic theory of Mathematical morphology, this paper proposes an accurate and highly robust method (ETH) for stray light suppression of space surveillance telescope, which is called the enhanced Top-Hat transform. Firstly, we define the Generalized Top-Hat transform according to the traditional Top-Hat transform. Secondly, we improve the background estimation of the traditional opening, introduce the closing to realize the multi-scale micro adjustment, and analyze the influence of the multi-scale micro adjustment on the stray light suppression and space weak targets segmentation. Finally, we introduce the noise suppression factor to reduce the residual noise in the stray light. In the field experiment, the method can effectively eliminate the interference of stray light, and greatly improves the local signal-to-noise ratio of space targets. It also shows that in a very low signal-to-noise ratio, this method can accurately and effectively segment space weak targets, and has strong robustness.

INDEX TERMS Stray light, weak space targets, morphology, noise, wide-field surveillance.

I. INTRODUCTION

With the development of science and technology, space exploration is becoming more and more frequent, and the number of spacecraft in orbit is increasing rapidly [1], [2]. More and more frequent space activities inevitably bring more space debris. A large number of space debris seriously endanger the safety of spacecraft and human space activities. Space environment surveillance is very important for space security [3], [4], [5]. Wide field of view and long exposure time space surveillance telescop can well detect weak targets in space, which will also bring more stray light interference to the imaging system [6], [7]. Stray light is one of the main factors affecting the performance of space optical payload. These stray light may come from the radiation of the sun, the moon, the earth's atmosphere and the instrument itself, which will cause a non-uniformity background when reaching the imaging sensor [8], [9], [10].

Even worse, with the signal-to-noise ratio decreasing, space weak targets signals was even completely overwhelmed by background and almost impossible to identify. which seriously affects the imaging quality and detection ability of the space surveillance telescop [11], [12], [13]. therefore, how to effectively eliminate stray light is very important for space environment surveillance.

In the process of space load design, stray light is usually suppressed through theoretical analysis and simulation. For example, Zhong [11] analyzed the range of solar incidence angle of the nighttime imaging Camera of Luojia-1 satellite and designed a special shaped baffle to avoid direct sunlight. Li [14] calculated the point source normalized irradiance transmittance of the Xinglong 2.16m telescope at different off-axis angles, identified the dominant contributors to stray light, and added only five vanes inside the bottom portion of the secondary baffle to improve its stray light suppression capability. Chen [15] analyzed the orbit characteristics and solar incidence angle distribution of Sun-synchronous orbit satellite, and designed a baffle to avoid direct sunlight.

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Despite the importance of stray light analysis during the instrument design phase, it is often difficult to completely eliminate the influence of stray light in the space surveillance only by relying on mechanical stray light suppression measures such as a baffle design, in the complex space environment. We need to further suppress the stray light by means of image processing technology, so as to obtain valuable space target information.

At present, there are many kinds of background estimation methods. Sparse representation [16], [17], [18] and robust principal component analysis [19] decompose the whole image under sparse and low rank constraints to realize background estimation. Wavelet transform [20] and Butterworth high pass filter [21] decompose the image through some frequency domain methods. However, these methods require a lot of computation and are not suitable for wide-field surveillance telescop. Common classical filtering methods mainly include max-median filter, max-mean filter [22], two-dimensional least mean square (tdlms) filter [23], [24], [25], morphological filter [26], [27] etc. These methods have unstable performance for low SNR images [28]. In order to solve this problem, Bai [29] proposed a new method based on the modified top-hat transformations, which reduces the sensitivity of the filter to stray light by introducing a threshold. Bai et al. [30] proposed a new top-hat transformation method, which realizes the multi-scale adjustment of top-hat transformation through two different structural elements. At the same time, the different information between the target area and the surrounding area is also considered. Deng et al. [31] optimized the structural elements of the top-hat filter by using quantum genetic method. The above methods have better performance than the typical filter methods, but they are still limited by stray light nonuniform background with strong noise, and can not achieve good detection results. In recent years, Xu et al. [32] proposed the INTHT method based on the new top-hat transformation to correct stray light nonuniform background for a wide-field surveillance system. Xu et al. [33] proposed the RMGM method based on recursion multi-scale grayscale morphology for wide-field surveillance. They all have achieved good results in stray light nonuniform background correction and stray light elimination, and basically achieved more accurate stray light nonuniform background elimination and high-precision target retention of the space surveillance camera.

However, for space weak targets, the removal of nonuniform background and the preservation of space weak targets can not achieve balanced processing. Some methods weaken and eliminate space weak targets while eliminating stray light. Some methods can not effectively remove the influence of noise in stray light background. More importantly, these methods can not accurately extract spatial weak targets from stray light background.

To solve these problems, we propose a high-accuracy and robust stray light elimination method called enhanced Top-Hat transform (ETH). Firstly, we define the Generalized Top-Hat transform according to the traditional Top-Hat transform. Secondly, we improve the background estimation of the traditional opening operation. Since the selection of the opening structure-elements is based on the targets in the space surveillance image, it is basically unchanged because of the function of the eliminate background generally. Therefore, we introduce the closing operation to preliminarily process the original space image. The closing operation can increase the multi-scale micro adjustment of the Generalized Top-Hat transform. The multi-scale micro adjustment will play a key role in the background stray light elimination and noise suppression in the space surveillance image. Finally, we define the noise suppression factor, which will effectively eliminate the weak noise signal submerged in the stray light background.

This paper is organized as follows: Section 2 analyzes the stray light effects on the performance of wide-field surveillance telescop with long exposure time. Section 3 describes the proposed ETH method. Section 4 presents the outfield experiments results of the ETH method. Finally, Section 5 summarizes the conclusions of this study.

II. IMAGING CHARACTERISTICS

A. IMAGING MODLE OF SPACE TARGET

The optical image is modeled as follows

$$F(i,j) = T(i,j) + S(i,j) + B(i,j) + N(i,j) \tag{1}$$

where $F(i,j)$ represents the image grayscale value at the space coordinate (i,j), $T(i,j)$ and $S(i,j)$ represents the space targets and stars, and $B(i,j)$ represents the space background, which is often nonuniform because of the effects of stray light. $N(i,j)$ represents the noise, including thermal noise, readout noise, dark current noise, etc.

The space target processed in this paper takes the star point as an example, and the energy distribution of the star point can be approximately expressed by Gaussian point spread function.

$$T(x,y) = \frac{T_0}{2\pi\delta_{PSF}^2}\exp\left\{-\frac{(x-x_0)^2+(y-y_0)^2}{2\delta_{PSF}^2}\right\} \tag{2}$$

where T_0 represents the total energy radiated by the star on the image sensor, $(x_0 - y_0)$ is the centroid coordinate of the star, δ_{PSF} is the Gaussian radius of the star point.

For ideal stars, the energy distribution of observation stars follows a two-dimensional Gaussian distribution, that is, the gray value of pixels in the star dispersion area is symmetrically distributed. In the dispersion area, the grey level of the target decreases gradually from the centre to the surrounding area.

B. ANALYSIS OF THE SPACE SURVEILLANCE IMAGE

The images used in this paper are taken by the space surveillance telescope. The detector is gsense6060 CMOS image sensor of changguangchenxin company, which has high quantum efficiency in the range of visible spectrum.

In order to facilitate the research, we choose the star point as the research target. When the signal-to-noise ratio of the target is lower than 1, we think it is a weak target in space. We obtained the space surveillance image through the outfield experiments, and selected three typical space targets with different energy. Among them, target 1 belongs to a space weak target, and the local signal-to-noise ratio is 0.1098. It can be seen that the target is greatly affected by stray light and is almost submerged in the background of stray light. Target 2 belongs to a target with slightly higher energy, and the local signal-to-noise ratio is 0.4483. It can be seen that the target is not only affected by stray light background, but also affected by dark current noise with higher energy. Target 3 is a space target with strong energy, which is less affected by stray light and more affected by dark current noise. The local signal-to-noise ratio of the target 3 is 1.0085. It can be seen that because of the characteristics of wide-field and long exposure, stray light and noise bring great difficulties to the detection of weak targets in space.

In this section, we analyze the features of space typical targets and stray light nonuniform background in wide-field surveillance image. Research on imaging characteristics is crucial to the performance of stray light elimination methods.

III. STRAY LIGHT ELIMINATE METHOD

A. IMPROVED TOP-HAT TRANSFORMATION

Mathematical morphological operations work with two sets:

an original image and structuring element [34]. Mathematical morphology operation is based on two basic operations: dilation operation and erosion operation. From dilation and erosion, the opening operation, closing operation and Top-Hat transformation in mathematical morphology operation can be obtained respectively.

For a grey-scale image, dilation and erosion operator can be defined respectively as:

$$f \oplus \Phi = \max\{f(i-m, j-n) + \Phi(m,n) \mid (m,n) \in D_\Phi\} \quad (3)$$

$$f \Theta \Phi = \min\{f(i+m, j+n) - \Phi(m,n) \mid (m,n) \in D_\Phi\} \quad (4)$$

where $\oplus$ and Θ represents the dilation and erosion, respectively. Φ represents the structuring element(SE), which is an important part of erosion and dilation operations. SE is a matrix with only 1s and 0s of any size and shape. Dilation makes the image gray value larger than that of the original image,which will also increase the size of bright region. Erosion makes the image gray value smaller than that of the original image,which will also decreases the size of bright region.

The opening and closing operations can be defined as:

$$f \bullet \Phi = (f \oplus \Phi) \Theta \Phi \quad (5)$$

$$f \circ \Phi = (f \Theta \Phi) \oplus \Phi \quad (6)$$

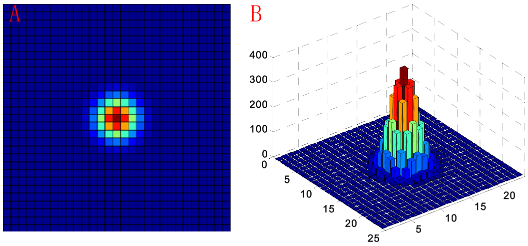

FIGURE 1. **(a) Imaging model of an ideal star, (b) 3D plot of a star.**

where $\circ$ represents the opening operator which can smooth bright small regions of image and $\bullet$ represents the closing operation which can eliminate dark small holes.

Then, top-hat transformation is defined by:

$$f_{TOP-hat} = f(i,j) - f(i,j) \circ \Phi \quad (7)$$

where $f(i,j)$ represents the original image. The classical top-hat transformation uses two same structuring elements, which has great limitations in the estimation of stray light background. It is often necessary to design a threshold to achieve the accurate segmentation of targets or stars. It is extremely difficult to choose an appropriate threshold for weak targets in space. Space weak targets are very sensitive to the selection of the threshold. Inappropriate threshold will weaken or even eliminate space weak targets. The current adaptive threshold method can not solve this problem well.

At the same time, threshold segmentation can not remove the weak impulse noise signal submerged in the stray light background.

In order to solve these problems and make the Top-Hat transform better applied to the space surveillance telescope, we improve the traditional Top-Hat transformation model. First, we define the Generalized Top-Hat transform model as follows:

$$f_{GTH} = (f(i,j) - T(i,j) \circ \Phi_\alpha) \otimes k \quad (8)$$

In our method, we use $T(i,j)$ to replace the original image. As shown in Eq. (9), we add a structural element to the Generalized Top-Hat transform by introducing the closing operation, which will bring a function of background suppression micro-adjustment. So we can eliminate the stray light background and keep the space weak targets more effectively. Compared with the traditional Top-Hat transform, our Generalized Top-Hat method can obtain a more accurate background estimation without threshold segmentation. At the same time, we introduce a noise suppression factor called K, in Eq. (10), as shown at the bottom of the next page. It will eliminate the residual weak noise signal in the stray light background further.

$$T(i,j) = f(i,j) \bullet \Phi_\beta \quad (9)$$

Then, the ETH method is obtained as follows:

$$f_{ETH} = (f(i,j) - f(i,j) \bullet \Phi_\beta \circ \Phi_\alpha) \otimes k \quad (11)$$

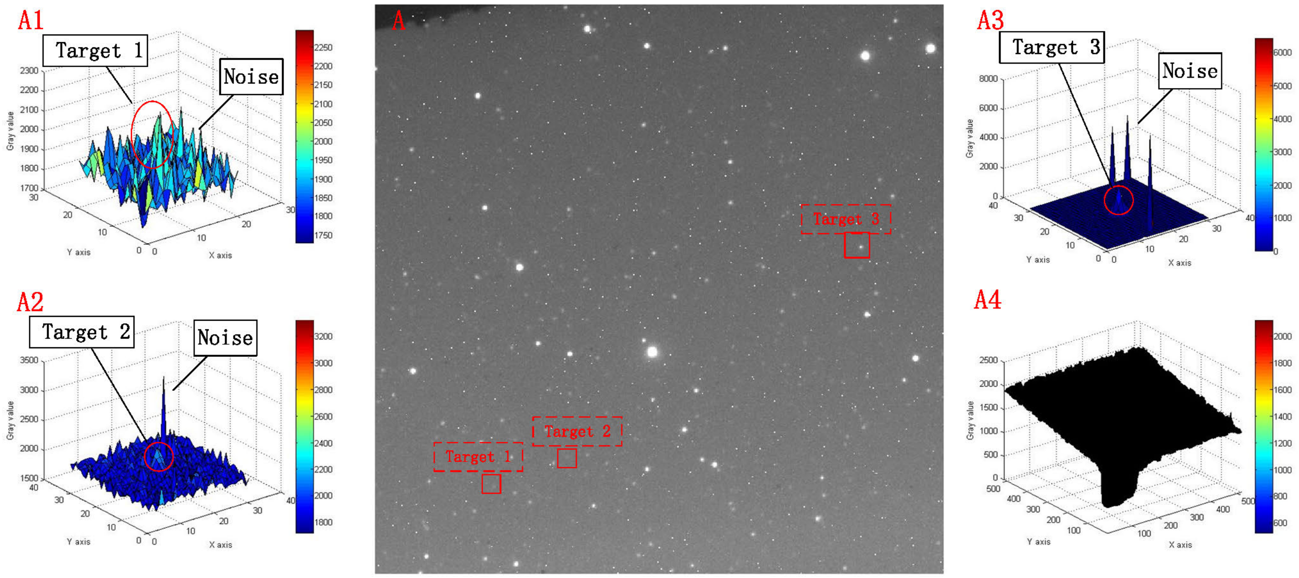

FIGURE 2. Influence of stray light on wide-field surveillance image in complicated situations. (A) Original surveillance image, (A1) Space weak target in surveillance image, (A2) Space target with slightly higher energy in surveillance image, (A3) Space target with strong energy in surveillance image, (A4) Nonuniform stray light background in surveillance image.

B. SELECTION OF STRUCTURING ELEMENT

This section mainly introduces the selection of the structural elements. Due to the introduction of closing operation, there will be four structural elements in the ETH method, two for opening, and the other two for closing. In order not to lose image information, the opening operation and the closing operation each use a same structural element. The opening operation is used for background estimation. The structural element of the opening operation needs to be slightly larger than the space targets as shown in Fig. 3. Closing operation is used to realize the function of background suppression micro-adjustment. The selection of the structural elements is usually the same as opening operation. However, when we care space weak targets more, adjusting the size of structural elements will help us better retain weak targets while suppressing stray light noise. This fine adjustment reduces the sensitivity of weak targets to the method. When we need to make the weak targets energy stronger, we can choose a slightly smaller structural element. When we want to suppress more stray light noise, we choose a slightly larger structural element.

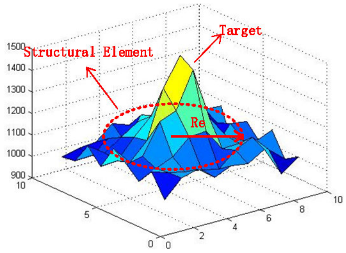

FIGURE 3. Used structural element in the proposed ETH method.

From the experimental results of space surveillance images as shown in Fig. 4, we can see the effect of background suppression micro-adjustment and we compare the results of traditional Top-Hat transform with ours to further prove the superiority of our method.

IV. EXPERIMENTS AND DISCUSSIONS

In this section, we compared the proposed ETH method with three other methods, including the classic method and the excellent methods in recent years, which are suitable for eliminating stray light in wide-field surveillance image. The compared methods are new Top-Hat transform method [30], INTHT method [32], RMGM method [33]. The core of wide

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$$f \otimes k = \begin{cases} 0, & \begin{cases} f(i-1,j)\,\&\,f(i+1,j)\,\&\,f(i,j-1)\,\&\,f(i,j+1) <= 0 \\ f(i-1,j)\,\&\,f(i+2,j)\,\&\,f(i,j-1)\,\&\,f(i,j+1) \\ \qquad\qquad\qquad\qquad \&\,f(i+1,j-1)\,\&\,f(i+1,j+1) <= 0 \\ f(i,j-1)\,\&\,f(i,j+2)\,\&\,f(i-1,j)\,\&\,f(i+1,j) \\ \qquad\qquad\qquad\qquad \&\,f(i-1,j+1)\,\&\,f(i+1,j+1) <= 0 \end{cases} \\ f(i,j), & others \end{cases} \tag{10}$$

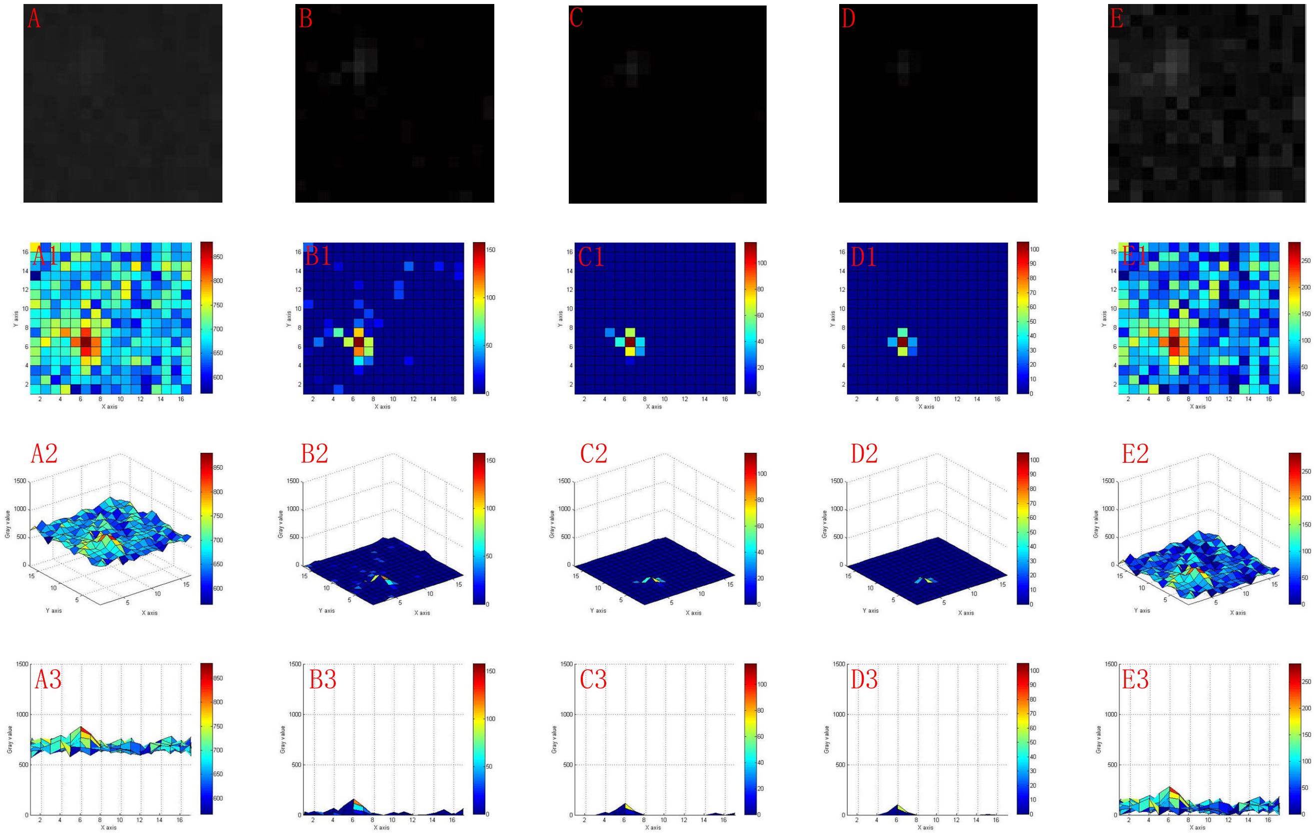

FIGURE 4. Stray light elimination result of our method and traditional method. (A)-(A3) Original surveillance images, (B)-(B3) Stray light elimination result of the proposed ETH method when the structural element is 4 pixels, (C)-(C3) Stray light elimination result of the proposed ETH method when the structural element is 8 pixels, (D)-(D3) Stray light elimination result of the proposed ETH method when the structural element is 12 pixels, (E)-(E3) Stray light elimination result of traditional Top-Hat transform.

field surveillance is to detect weak space targets, so the premise of experimental data analysis in this paper is to retain the weakest space targets in the image. Due to the multi-scale adjustment of some methods, the selection of structural elements will have a direct impact on the evaluation of experimental results. We select a space weak target with a local signal-to-noise ratio of 0.1 as the reference, because such a space weak target is the most sensitive to the selection of structural elements and the influence of stray light. By keeping the same energy value of the space weak target after different methods, we get the size of structural elements of different methods. We obtained 100 images from the outfield experiments taken by the space surveillance telescope. Firstly, we analyze the accuracy of stray light elimination of different methods by calculating the background residual. Secondly, we analyze the improvement of image quality of different methods by calculating the local signal-to-noise ratio of stars. When the background residual is smaller and the local signal-to-noise ratio of the star is larger, we think the performance of the stray light elimination method is better.

A. ACCURACY OF STRAY LIGHT BACKGROUND ELIMINATION

Some results of stray light non-uniform background elimination are shown in Fig. 5. In Fig. 5, (A)-(D) are the stray light nonuniform background of original surveillance images, (A1)-(D1) are the surveillance images affected by different stray light. (A2-D2), (A3-D3), (A4-D4) and (A5-D5) are the surveillance images after using different methods to eliminate stray light. It can be seen from the image that our method has lower stray light noise.

We use the method of background residual estimation to compare the strength of residual space background of different methods. Through data analysis, we can see that the calculation of background residual is consistent with the processing effect of different methods in Fig. 5. Our method has the smallest background residual, as shown in Table 1. So the performance of our method is better than other methods. That is to say, our method has the highest accuracy in eliminating stray light non-uniform background.

B. IMAGE QUALITY IMPROVEMENT

Stray light suppression is to improve the imaging quality of space camera. We analyzed the improvement of imaging quality of different methods after stray light suppression. From Fig. 6, we can intuitively see the processing effects of different methods. When the energy of the space target is strong, the original image is hardly affected by stray light, but will be affected by dark current noise. The new Top-Hat

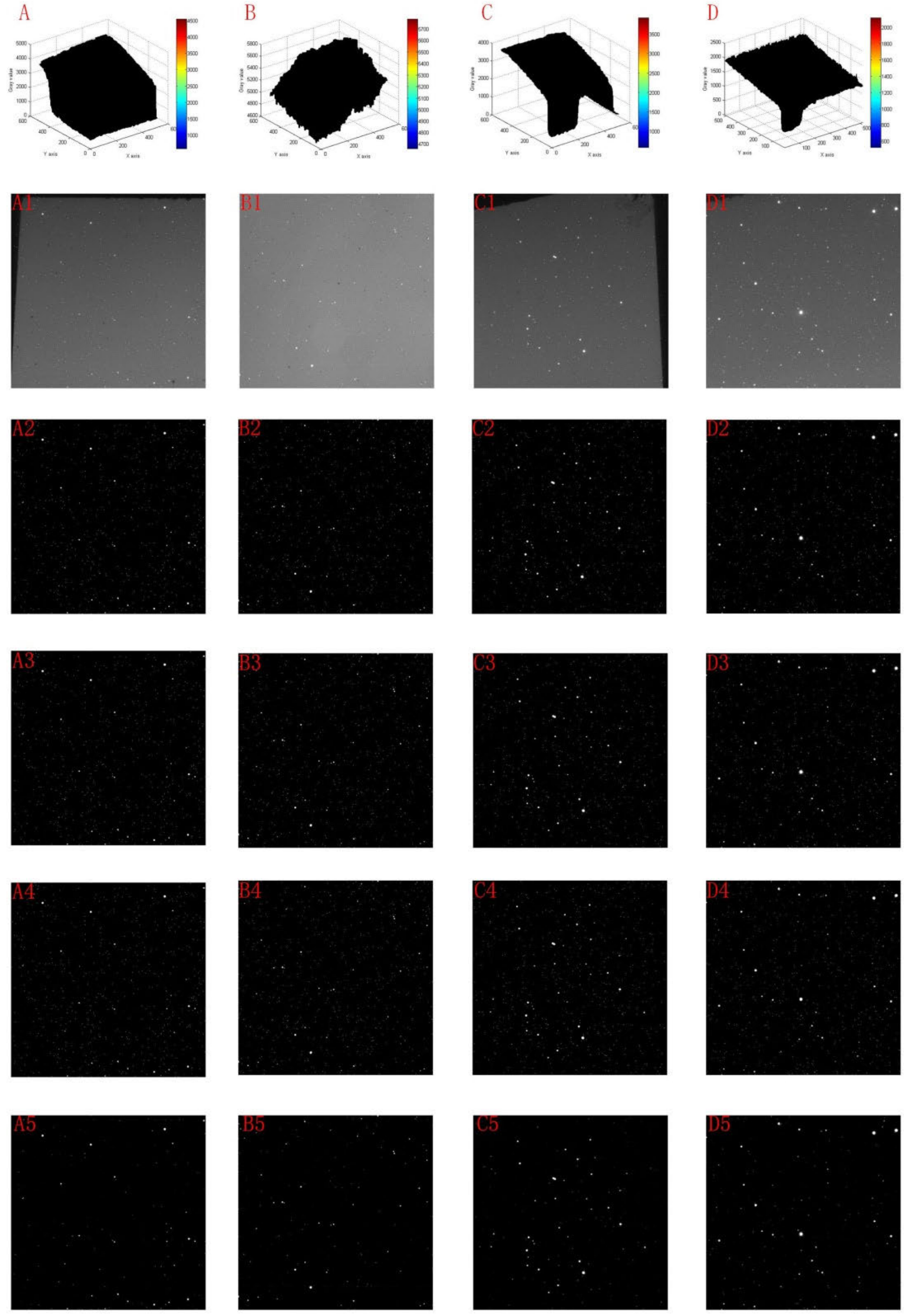

FIGURE 5. Stray light elimination result of different methods. (A)-(D) Stray light nonuniform background of original surveillance images, (A1)-(D1) Original surveillance images, (A2)-(D2) Stray light elimination result of the New Top-Hat method, (A3)-(D3) Stray light elimination result of the RMGM method, (A4)-(D4) Stray light elimination result of the INTHT method, (A5)-(D5) Stray light elimination result of the proposed ETH method.

transform, RMGM and INTHT can eliminate stray light background well, and the space background becomes smooth. But these methods can not eliminate the dark current noise with strong energy. The ETH method proposed by us not only eliminates stray light, but also removes dark current noise. When the energy of space target is moderate, it can be seen from the original image that stray light has some effect on the target. Compared with the target, the stray light noise is relatively large. Compared with dark current noise, the target signal is relatively weak. After processing of the new Top-Hat transform, RMGM and INTHT, it can be seen from the image that the target signal is retained, but some stray light noise

TABLE 1. **The results of the residual image mean and variance.**

	Method	RMGM	New Top-Hat	INTHT	The Proposed ETH method
Fig.A1	Mean	0.3416	0.3416	0.2326	0.0191
	Standard Deviation	3.0745	3.0745	2.5221	0.5210
Fig.B1	Mean	0.3847	0.3847	0.2607	0.0126
	Standard Deviation	3.2499	3.2499	2.6428	0.4070
Fig.C1	Mean	0.4109	0.4109	0.2729	0.0393
	Standard Deviation	3.5507	3.5507	2.8822	0.8717
Fig.D1	Mean	0.5739	0.5739	0.3677	0.1065
	Standard Deviation	4.3360	4.3360	3.4062	1.6314

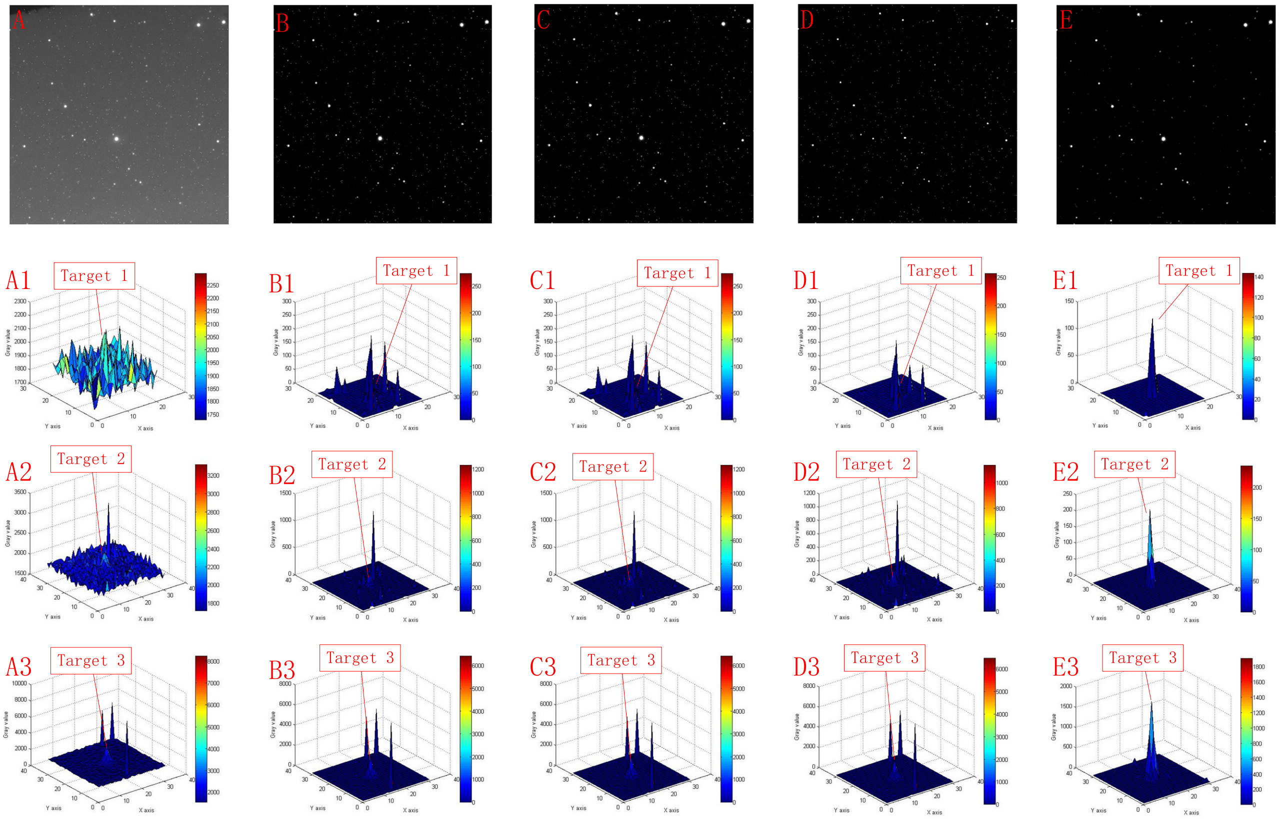

FIGURE 6. **Stray light elimination result of four different methods. (A)-(A3) Original surveillance images, (B)-(B3) Stray light elimination result of the RMGM method, (C)-(C3) Stray light elimination result of the New Top-Hat method, (D)-(D3) Stray light elimination result of the INTHT method, (E)-(E3) Stray light elimination result of the proposed ETH method.**

and dark current noise are still retained in the background at the same time. After the ETH method we proposed, the space background is very smooth, which shows that we not only eliminate stray light, but also remove dark current noise. When the energy of the space target is weak, it can be seen from the original image that the target is almost submerged in the stray light background noise. After the processing of the new Top-Hat transform, RMGM and INTHT, it can be seen that these methods can not separate the weak target from the residual stray light background noise. Our ETH method can still segment the weak space target from the stray light background almost perfectly, and the background is very smooth after processing.

At the same time, we obtained the local signal-to-noise ratio of different targets to quantitatively evaluate the image quality improvement of different methods as shown in Table 2. For target 3, when the signal energy is strong, the new Top-Hat transform, RMGM and INTHT can not effectively remove the dark current noise, so the local signal-to-noise ratio is not significantly improved. After processed by our

TABLE 2. Local signal-to-noise ratio of different methods.

Method	Target 1	Target 2	Target 3
Original image	0.1098	0.4483	1.0085
RMGM	2.9886	1.5138	1.1797
New Top-Hat	2.9886	1.5138	1.1797
INTHT	1.9606	1.2033	1.1098
Proposed method	Inf	21.3182	43.3235

TABLE 3. Computation time results of different methods.

Method	RMGM	New Top-Hat	INTHT	The Proposed ETH method
Time(s)	0.702701	0.465686	0.597303	0.573771

ETH method, the space background is very smooth, so the local signal-to-noise ratio is greatly improved. For target 2, when the signal energy is moderate, the local signal-to-noise ratio of the new Top-Hat transform, RMGM and INTHT is improved compared with the original image. Because some stray light noise and dark current noise are still retained in the background, the improvement of all signal-to-noise ratios is limited. After our ETH method, the space background is very smooth, so the local signal-to-noise ratio is greatly improved. For the target 1 with weak energy, new Top-Hat transform, RMGM and INTHT have significantly improved the local signal-to-noise ratio compared with the original image, because these methods remove most of the interference of stray light noise. After our ETH method,the local signal-to-noise ratio is infinite, which shows that the local space stray light background is almost 0. RMGM method is the application of the new Top-Hat transform. It takes the minimum value of the processed image and the original image as the stray light background, and adopts a recursion multi-scale method in order to ensure that large size stars and space targets will not be lost. When the structural elements of the two methods are the same, the experimental results are not any different. When selecting appropriate structural elements for background estimation, the background of the image processed by the new Top-Hat transform is larger than the background part of the original image because of the morphological dilation. The RMGM method takes the minimum value of the estimated background in the new Top-Hat transform and the original image as the stray light background. Therefore, for the relatively dark background of the image, the estimated background will be obtained by the subtraction between two original image. For the relatively bright noise part and target part of the image, the background estimated processed by the RMGM method and the new Top-Hat transform are the same, so the results of the two methods are the same. We can see intuitively from Fig. 5.

C. COMPUTATION TIME

In order to compare the calculation time of different methods, all methods implemented in matlabr2012a and PC specification include an i5-6500u (2.30ghz) and 8GB main memory. The image size is 512k × 512 pixels. The calculation time of different methods is shown in Table 3. Different methods are based on the improvement of morphological filtering. From the calculation time, it can be seen that there is little difference in calculation time.

V. CONCLUSION

In order to solve the problem that the existing methods can not accurately eliminate the non-uniform stray light in space surveillance images, we propose an enhanced Top-Hat transform (ETH) method. This paper first analyzes the effect of stray light on the imaging of wide-field surveillance telescope under the condition of long exposure time. And then we introduce the principle and surveillance images processing effect of the enhanced Top-Hat transform (ETH) method. By defining the mathematical model of Generalized Top-Hat transform, we introduce the closing operation into the traditional Top-Hat transform model, so that the Top-Hat transform will have the background suppression micro regulation function. When processing space images, the ETH method will get a better balance between retaining targets and stray light suppression, and can better eliminate stray light and segment target. We also introduce the noise suppression factor into the Generalized Top-Hat transform to further suppress the stray light noise and make the space background smoother. The efficiency and superiority of our proposed ETH method is verified by the images taken by the wide-field surveillance telescope in the outfield experiments. Compared with other methods, this ETH method achieves higher stray light elimination accuracy and better image quality improvement effect. Most importantly, in the case of very low signal-to-noise ratio, it can accurately extract the space weak target signal submerged in the stray light background.

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