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High accuracy measurement of the MTF of electro-optical Imaging System

Based on Modified Slanted-edge method

Li hang[1] ,[2] ,Yan chang-xiang [1] , Shaojian-bing ,Wang xiaopeng
[1] Changchun Institute of Optics, Fine mechanics and physics,Chinese Academy Science,Changchun 130033 , ,

[2] University of Chinese Academy of science, Beijing 100049 , the

Abstract: In This study , an improved slanted Edge method was proposed . It had a High accuracy for measuring Modulation Transfer Function (MTF"of") electro-optical imaging system. We put forward an automatic Determination of the High and low thresholdmodified Canny operator to detect the Edge points , and Edge slant angle is obtained by linear fitting to the edge points . In Process to fitting The edge spread function (ESF) by Fermi function , We put forward a modified method to reduce the Influence o noise. It was composed The averaging in adjacent region and setting this tolerance to error. The Method In this paper is proved efectively by E x perimental results, and analyzing This influence to the Change To the [] Edge slant Angle then noise on this MTF measurement accuracy. The e xperimental results show that on Measurement accuracy of on modifiedslanted Edge method s 0.004 9, and The Repeat accuracy s 0.003 1,which s higher than this Traditional methods. It proves that the Modified slanted Edge method has High measurement and repeat accuracy, and also has a better immunity to noise , and Edge Angle.

Keywords: Imaging Systems; modulation transfer function ; Noise ; Modified slanted-edge method ; Edge angle; Edge spread function

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The improves the ESF fitting accuracy ; Last , through emulation and physical real , The traditional method and the method of this paper are tested and analyzed .

How to accurately evaluate the performance of optoelectronic imaging systems for this system is important in the design , processing and Applications .modulation transfer func-

tion (modulation TTRANSFERFUNCTIORUMLF) is evaluation photoelectric One of the key indicators of spatial frequency transfer characteristics of a system ,whose value is from diffraction effect of a photoelectric imaging system , image difference size and probe attributes are with decision [1]. MTF To verify that the system's actual

performance is close to the The design goals are very important , existing MTF test method main is divided into two categories :1) Using random target test [2], This method can effectively Resolve system due to sample problem , but difficulty with target processing , Data Processing is cumbersome to restrict its application ; using fixed graphics target test [3], main application slit targets and edge targets . Chambliss equals 1995 Year proposed slit test MTF principles and specific procedures [4], but is a slit target that is difficult to make. , different systems need to use different narrow target , and test results should be corrected according to slit width . Tilt Edge Law has a target commonality strong , High Data sample rate , test procedure simple Benefits , widely used in various optoelectronic imaging Systems MT F test , and by international standards is 0 12233 Specify as electronic static image camera standard method for resolution test 5 . Li Tiecheng [6] , Zhao Jinping [] should The optical remote sensing load on the orbit with the tilt edge method MTF tested ; Peak etc [8], Shaolun, etc. [9] Apply Tilt Edge method to medical imaging collar field digitization X radiographic System Performance evaluation .

to test a photoelectric imaging system using a tilt edge method MTF of Process , test procedure vulnerable to noise disturbances , Edge Tilt measurement error than large, edge spread function (Edge spreadfunction ,ESF) extract No [low accuracy , to cause the system's MTF test less accurate . Zhu log, and so on TM proposed with an improved HoughTransform extract edge angle , improves operation speed , but Hough The accuracy of the transformation is subject to its parameters Effects of amount Space manual quantification ;Masaoka wait [one] propose a two-dimensional function Fitting Edge image estimation method for edge inclination of edges , This method has better anti-noise ,However, function fitting is affected by discrete pixels , make The estimation accuracy of edge dip is not high , With a large amount of calculation . ya (1) , and so on ^2proposes a combination of Gaussian and exponential functions to fit the ESF side method ;tzannes , and so on [@] proposes to use the Fermi function to fit the ESF Method , The fitting method for these ESF is susceptible to noise effects , make ESF fit Less accurate . fan Chong [i] based on gradient and point spread function symmetry presents a new edge fitting method , and ESF Sample Data Enter A certain amount of noise removal is done , to estimate accuracy and stability Improved . Li jin [m] A parameter model based on system transfer function is proposed type ESF Build Method , increased ESF build accuracy , then Improved system MTF estimate accuracy .

problems with the traditional tilt edge method , This article provides a benefit an improvement to automatically determine high and low thresholds Canny edge detection operator extract Edge point , linear draw Edge location point Edge inclination measurement for edge inclination ; to the Fermi function The procedure for the close ESF is improved , proposes effective noise reduction ,

1. MTF measuring Principles and methods

1.1 MTF measuring principles for

MTF Is the system's sine-wave target for different spatial frequencies Quantitative response , sine wave target light brightness along space a certain direction week Period change , set lightest brightness to Im « , Darkest Brightness is Imn . is To express the degree of intensity of the image , define system to

M = Wide °+, mn (1)

Max I min

System Imaging The modulation system should be lower than the regulation of objects , definition modulation transfer function to indicate the degree of reduction of imaging Pre-and backward modulation system , frequency The modulation transfer function at the rate /is /

=M_ge (/)

- M_rB_{lect} (F)

type , M ^c The modulation of an object , M _ge represents an image modulation .

Press MTF definition of , can directly use the sine wave target test system's MTF, But considering the processing difficulty of the sine target , general through

Indirect measurement point diffusion function (Point spread Function , PSF), Line diffusion

function (Line spreadfunction ,LSF) / ESF to find

The system's MTF . The point pulse method provides a light point for the imaging system Source Input , brightness distribution function After system imaging is PSF , to PSF for a two-dimensional Fourier transform to get the system's MTF , that

MTF («, and v)- \ F [_PSF(x,, y)] | (3)

The Slit method provides an optical line to the imaging system using a slit target Source Input , Its imaging brightness distribution function is LSF . Line light can be to view the set of point light sources along the slit direction , so PSF along the slit direction integral that is LSF, to LSF to make a Viffoury leaf transformation to to be perpendicular to slit direction MTF, Its relationship is

LSF (c)-] PSF (c,y)d_y (4)

MTF («,0)- | F [LSF 0 r] | (5)

The Edge method of the is to provide a step for the imaging system using the edge target . Enter , Its imaging brightness distribution function is ESF,ESF and LSF The relationship between is

LSF (work)- D [ESF(workers)] (6)

Is provided by the type (6) unknown ,LSF for ESF derivative , so edge measurement try MTF based on edge image extraction ESF, to ESF derivation LSF, then LSF for Fourier transform system MTF · diagram 1.

1.2 is 0 12233 Tilt Edge method

is 0 12233 Tilt Edge method is an electronic static image camera MTF Standard methods for testing , The primary procedure for testing is : On the edge of the collectionimage Select Edge Area for calculation (Regionofinterest, R0 I); calculates each line in the selected range ESF the derivative of the data , To obtain LSF; calculates each line in the selected range LSF Center of gravity for , is each line Edge positions , line all edge position points fitting for Edge inclination ; Calculates the rows contained in each phase cycle number , Resize selected area , The contains the entire number of phases for the selected range cycle ( ) all pixels in the selected range are projected along the edge of the page 1 line , take original sample interval 1/4 as new sample interval , to every The pixel grayscale values in the sampling interval are averaged , and gets an average of - like ESF ; to sample an average of ESF derivation to get an average sample LSF; uses the Hamming filter to LSF for processing , and do the FU in-leaf transform to fetch MTF. is 012233 Edge tilt of edge Edge method The angle calculation calculates the Center of gravity of the LSF after derivation of each row of data set , avg Sample LSF access is also done by averaging the ESF derivation , which causes this method to be susceptible to noise in edge images scrambling Lower System MTF test accuracy .

2. This article method

to test a photoelectric imaging system using a tilt edge method MTF of process , precise measurement of edge inclination ,ESF The exact extraction has been the dumpingKey points and difficulties of oblique edge method . This article analyzes the base of traditional methods ,, an Improved tilt edge method is proposed to ensure edge inclination measurement volume vs . ESF Extract Accuracy , to Improve photoelectric imaging system MTF Test accuracy .

2.1 measuring method for edge inclination

The traditional tilt edge method first uses the differential edge detection operator to place the Edge image , But first order , Second-order differential edge detection operator pairs with edge detection of edges with noise , and Canny Edge Detection operator with large Snr , positioning accuracy High , single edge response good Benefits ,is an operator that is approximately optimal for step edge detection . but is , take advantage of Canny operator for edge detection , needs to artificially set the High and Low thresholds to filter edge points , set different heights for the same image thresholds have significantly different edge detections . For The Photoelectric imaging systemautomatic measurement of edge angle of edges collected by the edge image , Avoid people affect setting conditions , It is proposed to use an adaptive Canny operator for edge detection , can be based on the characteristics of the edge image automatically get

the best high and low thresholds .

The best criterion for separation among different classes is the in the sense of mathematical statistics class Variance maximum or within class variance minimum , so , The specific implementation of the algorithm is the use of gradient amplitude histograms and minimizing class variance . Edges Chart The gradient amplitude of pixel grayscale in the image is divided into m level , and divide pixels into C1 . C2 . C3 three classes . Ci The represents the non-marginal pixel of the image , Corresponds to a gray degree gradient is U,/ 2 , ..., ^ } Pixel point ,C2 represents an image may be edge dot pixel , corresponding grayscale gradient amplitude to U_{Si+}i , ^ $_{i+}$2 , ...,,} pixel of , C3 represents an edge point pixel in an image , Corresponds to a gray degree gradient is ,+ 1,, +2,...,} Pixel point . gradient Amplitude for , and for The number of pixels , The total number of pixels in the edge image is N . C1. C2 . C3 the gradient amplitude for each type of pixel is

The expressions that can be evaluated within the class are

^{k}1

G ^{2}(kD {)' { ^ ^ (is 1)]^{2} name + ^ [,-

i- 1 i- Yes 1+1

& (1 , Mimiko 2)], + public ,-,^ (2)]^{2}i/n (8)

I - is 2 +1

satisfies the through a search solution mm [G(8)1 times)] & 2 value , then C, C2 The total number of pixels in a total pixel percentage is high threshold , C The percentage of pixels in the that counts as a total pixel is a low threshold . using automatic determine high and low thresholds Canny edge detection operators tilt edge image convert to edge two value image , Edge position point of extraction to line , then The edge inclination is obtained by linear fitting of all the position points of the edges .

2.2 ESF Extraction Method

ESF The extraction accuracy of is related to subsequent LSF , MTF calculation accuracy , so , How to more accurately base a collection on the edge of the edge Image extraction ESF is guaranteed for MTF The test accuracy of is very heavy for . is currently , ESF The extraction methods for are mainly divided into two types of : One is a straightto work with row data in edge regions [5] ; Another is a benefit fit discrete data with function model ESF[13] . is 0 12233 pour Diagonal Edge method ESF processing is the first method , using skew The small angle between the edge and the scanning direction is formed between different scanned rows. Minor phase shift features , resolved traditional edge edge method ESF Low sampling rate question , the specific method is to fit all the pixel points in the edge region along the The edge direction of the is projected to the direction perpendicular to the edge of the blade , fetching sample interval 1/4 As the new sample interval , for each sample interval pixel grayscale values are averaged , To get an average sample ESF , its pixel projection process diagram 2 .

But in the actual photoelectric imaging system MTF During the test process because of the tilt edge image affected by noise , blind thousand disturbances , The uses the preceding ESF To extract a method , noise causes edge-spread curves to fluctuate violently , Blind meta causes edge-spread curves to appear sharp peaks , Valley , and then differential for ESF LSF amplifies noise disturbances , to cause system MT F Low test accuracy , repeat bad . so , This article chooses to take advantage of the function model fitting discrete data extraction ESF method , and change to Enter , To increase its ESF Extraction Accuracy . The function model takes a more The Fermi function for strong noise suppression , considering actual edge diffusion curves generally asymmetric , Use a linear combination of three Fermi functions to get better fit accuracy , function expression is

F (x')^ 2 ---------- - Yd (9)

"L + Exp)

The specific improvement method is :

1) edges all pixels in Edge area (Chart 2 in ^ axis Direction) Project to ^ Axis , to the ^ the position on the axis is sideways superscript , with normalized grayscale values as ordinate , can get edge spread curve data point set ;

2) taking into account that the edge image of the collection is noisy , blind element effect , Edge margin diffusion curves may have large fluctuations with sharp peaks ,Valley , so , Direct utilization of Fermi function fitting is not good. , filter Blind meta to more Noisy points . divides the edge diffusion curves into dark areas and bright regions , with style (ten) work with ,,

y . ^ y. | y , (ten)

-- i+2

type , y is the coordinate point A The gray mean value of the neighborhood , y $^{=}$,

^ ,-i-2

k The value is based on the noise , for blind metadata , will satisfy the (Ten) , like, dot Gray values with neighborhood grayscale mean instead of , can be effectively filteredremove blind elements and noisy points ;

3) using a nonlinear least squares fitting method , on data using Fermi function model Fit to get ESF, The of each pixel point error | F (A)- y , I , Eliminate error 0 k2f (A) Point, k 2 Is the factor that is based on the noise situation. , and then the previous method The data is fitted to the final ESF . this ESF has been extracted Threads take advantage of multiple denoising methods , can effectively improve ESF extraction accuracy .

3. Experimental test and analysis

3.1 emulation Experiment 3.1.1 Design of simulation experiment

to analyze the improved tilt edge method proposed in this paper , has an imitation True experiment to this article method , Traditional method [],ISO 12233 methods [5]and The improved methods presented in the document [14-15] are tested in contrast . in imitation True Experiment , First Take advantage of Matlab software Generation X like Meta the ideal tilt edge image ; the ideal tilt edge image with the known P SF for convolution operations , simulating the blur effect of a real photoelectric imaging systemshould ,PSF Use Gauss function to simulate , Its expression is

1 R (A + y +))

PSF ($_{C}$,y)= 2 ^ 2exp [$^{(}$2 [/]/] (1)

type , To 5=0. 5, based on the type (3) You can find the of a tilted edge image theory M T F curve , and use it as an evaluation benchmark ; last , add white noise to the edge of Edge side image . to change the tilt edge chart during testing Image edge inclination and noise level , using signal-to-noise ratio (Signal to noiseratio , SNR) size representation , Analyzing various test methods Blades Effect of edge inclination and noise . diagram 3 for Edge dip to 9°, SNR is DB Tilt Edge image for .

diagram 3 Edge angle is 9 °, SNR is DB Tilt Edge image for

Fig. 3 The image of Slanted-edge with edge angle of 9°and SNR of DB

3.1.2 Edge Angle Measurement method comparison

Use the edge angle of the edges to 9 . ,SNR ,, 30dB ,40dB and DB The simulated tilt edge image of the is the measuring square for different edge angles of edges Comparison analysis , edge inclination measurement methods mainly have literature [0] improvements made by Hough Transform , Documentation [1] Two-dimensional proposed by number fit ,ISO 12233 Method ,Documentation [4] gradient and proposed by Point spread function symmetry method and the improvements presented in this article Canny Count Child combined with line fitting ,Measurement results and ideal edge tilt corner 9° The relative error of is shown in table 1.

Table 1 measurement results for different edge inclination measurements Table 1 The results of different edge angle testing Methods

Method	9°		
	DB	DB	DB
Ref. [10]	3. 37%	2. 86%	2 23%

Ref. [11]	1. 24%	1. 15%	1 12%
ISO 12233	4. 13%	3 8%	2 11%
REF [14]	1. 09%	1 4%	0 97%
Modified method	0. 98%	0 94%	0 92%

Documentation [ten] improvements made by Hough The transform method is empty by parameters Effect of manual quantization between , edge inclination measurement accuracy general ; document [All] proposed two-dimensional function fitting tilt edge edge image extraction Edge angle The method has high measurement accuracy and noise resistance , but fitting over more verbose ; ISO 12233 The edge inclination of the method is measured more accurately than Low , and the method contains a differential operation , So measurement accuracy is susceptible to edges edge image noise Change effect ; document [?] The edge-fitting side of the proposed method has better accuracy and noise resistance , But the fitting process is slightly complicated ; this In this paper, the method of measuring edge inclination is realized automatically Cannycount the high and low thresholds of the child , uses the Canny for step edge detection by the operator The combination of excellent performance and straight line fitting improves the measurement of edge inclination . Accuracy and noise resistance of the method , is a simple , High Accuracy , anti-noise Good angle measurement for edge angles .

3.1.3 MTF Measurement method comparison

The uses simulation experiments to compare and analyze the proposed improved tilt edge method ,is0 12233 method , document [[] Traditional methods and documentation presented by " MTF" for improvements proposed in [14-15] measure effect , main from MTF measuring accuracy , Measuring repeatability accuracy and measurement accuracy by the blade Edge dip , the extent to which the impact of noise changes is evaluated . First , Live into - edge angle to 9°, SNR is DB Tilt Edge Chart forlike , White noise distribution differs for each image . uses the above 5 type MTF test method test for Tilt edge image , MTF measure Quantity accuracy is expressed as

type ::= 1 , ..., m , m = 100,<:1 Express J measure MTF Measurement accuracy ;,y and V indicates the test received MTF Curves and slopes edge image theory MTF Curve same space frequency point corresponding to 卩 value ; the indicates the number of points to calculate when ; a represents A m measure get MTF measurement accuracy average ,The used by to represent the test method MTF measuring accuracy . MTF The measurement repeat accuracy of can be expressed as

type : V indicates that the test gets the m Bar MTF The average value of a curve line ;a MTF measure repeat accuracy for test methods . for Edge margin angle is 9°,SNR is DB Tilt Edge image for , 5 type MTF The measurement results of the test method are shown in table 2 .

Table 2 different MTF measurement results for test methods

Table 2 The results of different MTF testing methods

Method	A	A
ISO 12233	0.019 2	0.018 5
Ref . [A]	0 . 008 6	0.006 3
Ref . [A]	0 . 006 2	0.004 5
Ref	0.007 5	0.005 8
proposed Method	0 0049	0.003 1

from the table 2 The results analysis of shows that , compared to is 0 12233Method , document [[] Traditional methods and literature [14-15]proposed in forward Method , the Improved tilt edge method proposed in this paper has a high MTF measurement accuracy and repeat accuracy ,,respectively 0.004 9 and 0.003 1.

to parse the For each method MTF measurement accuracy edge tilt Corner , impact of noise changes , to generate two sets of tilt edge images : page 1 group Tilt Edge image SNR all 40 dB, edge angle, respectively is 5. , 10°, 15°, 20°,

25°; The Edge tilt of the second group of Slanted Edge images Corner to ten °snr for | DB , DB , DB , DB , DB . tilt Edge images are used in each condition To fetch the All methods MTF measurement accuracy , 5 of the method MTF measure Quasi Accurate Edge dip , effect of noise changes as shown in diagram 4,, 5.

diagram 4 SNR is DB MTF measurement accuracy varies with edge inclination of edges Fig. 4 The results a measurement accuracy to MTF With "" Change to edge angles at the SNR of- DB

diagram 5 Edge angle is 10° MTF measurement accuracy varies with noise Fig. 5 The results a measurement accuracy to MTF With "" Change to snrs at edge angle of 10°

Comprehensive analysis diagram 4, The results of the measurement are known as , is 0 12233 Method , MTF measurement accuracy lowest , and easily subject to edge inclination and noise effects . its Edge dip extraction process contains a differential operation , causes its noise . increases with edge inclination , its discrete ESF edge of edge position get less drop of projection data , This will make it process noise more sensitive ; Document [@] The traditional method proposed by IS edged dip and noise changes are weaker, but still affected , mostly because its procedure contains differential operations , and simply use fenrn function fitting ESF, No valid noise reduction ;document [15] Use System transitive function parametric model for ESF build , Improve system MTF measurement accuracy , However, the build accuracy is still affected by noise and edge The effect of tilt change ; Documentation [?] The presents a new edge-fitting method , and on the construction of ESF for some degree of noise removal ,make

MTF improves measurement accuracy and stability ; This method uses the Improved Canny operator and line fitting extraction edge inclination , in the ESF Fitting a valid denoising method , The therefore makes this this party has a higher MT F measurement accuracy , and almost no edge inclination and noise change effects .

3.2 Infrared Imaging System test

to verify the usefulness of the improved tilt edge method proposed in this article , in Lab built from Blackbody emitter , target , Parallel Light tube , Infrared The experimental platform for devices such as imaging Systems , as shown 6.

diagram 6 IR Imaging System MTF Test Appliance Fig. 6 The setup of testing the MTF of infrared imaging system

to accurately evaluate the improved tilt edge method , ISO 12233 Method , Text offer [ ] Traditional methods and documentation for [14- "] " method MTF test measure accuracy , require IR imaging system true MTF curve , and use it as an evaluation benchmark . for this , The measured the optical elements in the experiment Parts curvature radius , thickness , adjust interval and refractive index of optical materials, etc. amount , test process for refractive index of optical materials as shown in diagram 7.

diagram 7 Material Refractive index test

Fig. 7 The testing of material refractive index The takes the measured parameters into the optical design software to calculate the optical system's MTF curves , probe MTF curves by type (14) meter calculate , that is

$mtfd_{ete}E$, "$_R$ " = SMC (^^) sinc)

J SX J " sy " (NO)

type , and eight space-frequency , Ruler and /. to sample for probe frequency . to eventually find the IR imaging system's MTF Curve , As shown in figure 8 .

The uses a step target to obtain a tilt edge by imaging the infrared Imaging system image , Chart 9 is the actual tilt edge chart captured by the IR imaging system like ,the dotted line contains the range selected MTF Test valid zone field . to change the tilt of the target , To generate tilt edges with different edge angles edge image , with diagram 8 for infrared imaging systems in MTF The curve is the base , use ( ) to get different MTF measurement methods MTF measures - accuracy , test results see table 3.

diagram 9 Tilt Edge image

Fig. 9 The image of Slant edge

Table 3 different in IR imaging system testsMTF measurement results for test methodsTable 3 The results of different MTF testing methods In testing infrared imaging system

Edge Angle	0\				
	Iso 12233	Ref. [13]	Ref. [14]	REF [15]	Proposed Method
4. 02°	0.018 8	0. 008 1	0. 005 6	0. 006 6	0.004 7
9. 53°	0.019 8	0. 008 5	0. 006 0	0. 007 3	0.004 8
36°	0. 020 7	0. 009 2	0. 006 7	0. 008 0	0.005 0
52°	0.022 1	0. 009 8	0. 007 3	0. 008 9	0.005 4

from the table 3 The results analysis of shows that , compared to ISO 12233 Method , document [[] Traditional methods and literature [14-15] improvements made bymethod , Improved tilt edge method with higher MTF test quantity accuracy and good stability .

3.3 Space Remote sensing image restoration

Usually the recovery process for remote sensing images is through the extraction of remote sensing images of the MTF to restore the system PSF , and with PSF As System degradation letter number to restore remote sensing images . so , can be used to restore remote sensing images The effect indirectly evaluates the nature of the improved tilt edge method proposed in this paper to . in the experiment, the remote sensing image of a space optical remote sensing payload is selected as the

The original image , As shown in figure Ten .

diagram Ten Original Remote sensing image

Fig. Ten The original remote sensing image Add noise to the original image , and with a known P SF convolution artwork like , to degrade the original image as shown in the picture one .

diagram II Degraded Remote sensing image

Fig. One The degenerated remote sensing image The uses the is 0 12233 Method , Documentation [A] Traditional methods of , document [14-15] method proposed and improved tilt edge to Test degraded remote sensing images MTF, then take advantage of the test. MTF Estimate PSF, last , Uniform use of Wiener filtering method restore degraded remote sensing image . An evaluation base of the original remote sensing image , uses both Square error (Mean squared Error , MSE) and peak signal-to-noise ratio (Peak Signal tonoise Ratio , PSNR) These two parameters to evaluate The undo effect of the the price remote sensing image , See table 4.

Table 4 different MTF The Undo effect of the test method

Table 4 The restored results of different MTF testing methods

Method	Mse	Psnr
ISO 12233	48.751	31 251
Ref. [13]	39.437	32.172
Ref. [14]	34.065	32 887
Ref. [15]	37 184	32 403
Proposed method	31.236	33 184

from the table 4 The results of the are known as , compared to other 4 Method , using this The Improved tilt edge method obtains better remote sensing image restoration effect , This indirectly proves the improved tilt edge method proposed in this paper has a higher MTF Measurement accuracy .

4. Conclusion

for traditional MTF The test method has insufficient , This article presents the An improved tilt Edge method , mostly with improved Canny Count The Child combined with line fitting improves the measurement accuracy

of edge inclination and the noise resistance , to fit with ferirn function The procedure for ESF has been added with the Effective noise reduction , guarantee ESF fitting accuracy of . use emulation experiment , IR Imaging System test and Remote sensing image restoration Experiment Verification The validity of this method , Experimental results show that : compared to is 0 12233 methods , Documents [A] proposed traditional methods and documents [14-15] Improved Method , This method has a higher M T F [] Measure exact degree and repeat accuracy ; , This method has better noise resistance , and the measurement result is essentially unaffected by the change of edge inclination .

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