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Evaluation of infrared collimators for testing thermal imaging systems

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Infrared reflective collimators are important components of expensive sophisticated test systems used for testing thermal imagers. Too low quality collimators can become a source of significant measurement errors and collimators of too high quality can unnecessarily increase cost of a test system. In such a situation it is important for test system users to know proper requirements on the collimator and to be able to verify its performance. A method for evaluation of infrared reflective collimators used in test systems for testing thermal imagers is presented in this paper. The method requires only easily available optical equipment and can be used not only by collimator manufactures but also by users of test equipment to verify performance of the collimators used for testing thermal imagers.

Keywords: IR systems, testing thermal imaging systems, IR optical design.

1. Introduction

IR collimators are typical elements of laboratory sets-up used for testing thermal imaging systems. Reflective two-mirror collimators built using an off-axis parabolic collimating mirror and smaller directional flat mirror represent a typical design (Fig. 1). The function of the IR collimator is to generate a thermal image closely resembling the thermal scene at the test plate. In its ultimate form, an ideal IR collimator would be capable of generating a radiation pattern that exactly reproduced the real image. However, such quality is unattainable. Instead, a practical design condition should be adopted, based on the requirement that the collimator spatial resolution should match the spatial resolution capabilities of the tested thermal imager.

Although IR collimators are frequently used for testing thermal imagers since the 1970s, there has been little interest in a problem of evaluation of these optical systems. Only a few general guidelines of limited usefulness in practise have been published [1–3]. A more precise condition for the spatial resolution of the IR collimator for testing thermal imagers was published in Ref. 4. However, it is quite difficult to use this condition for evaluation of real collimators of unknown parameters. Next, the condition should be updated

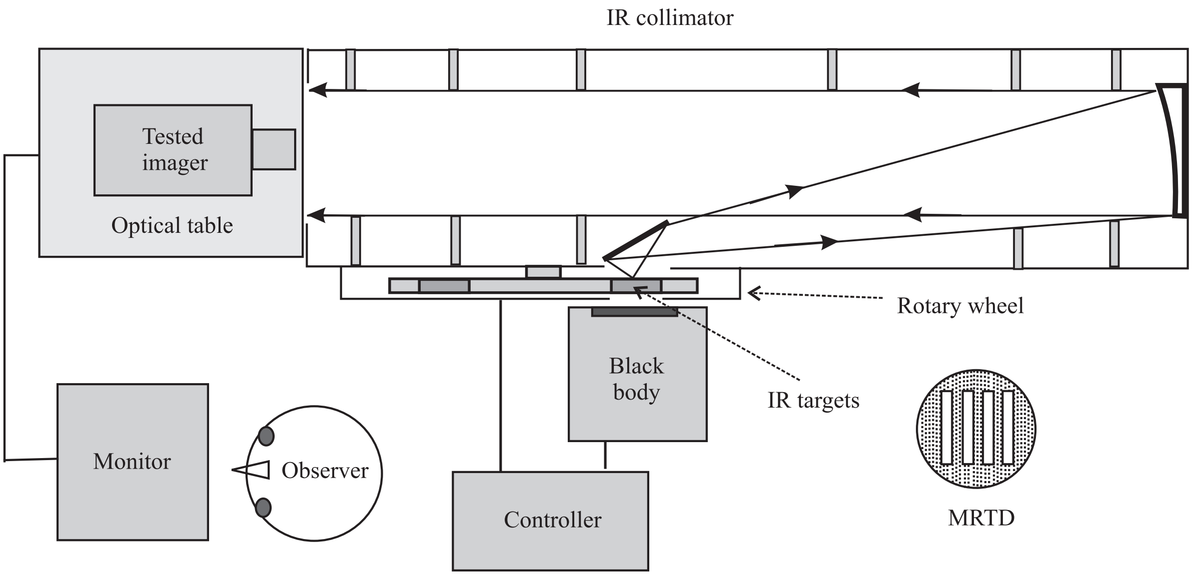

Fig. 1. Typical block diagram of a system for testing thermal imagers.

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as it refers to a definition of spatial resolution unsuitable for modern third generation thermal imagers. It can be used only in case of some older, first or second generation, imagers designed using scanning technology.

Manufacturers of IR collimators use different methods to characterize performance of these systems. However, all these parameters like mirror accuracy, diffraction blur, geometrical blur or resolution can be treated as indicators of possible collimator quality but are not measurable parameters that would give warranty about quality of collimator at the user hands.

A simple method for evaluation of the IR reflective collimators to be used for testing thermal imaging systems is presented in this paper. The method requires only easily available optical equipment and can be used not only by collimator manufactures but also by the users of equipment for testing thermal imagers to verify performance of the collimators that are vital components of the test equipment.

2. Characterization of IR collimators

Manufacturers of IR collimators use different methods to characterize performance of these systems. Accuracy of manufacturing of the collimating mirror is typically presented as a collimator parameter [5]. However, manufacturing accuracy of the mirrors is not very useful if we really need to evaluate quality of the collimator we want to use in testing thermal imagers.

First, perfect mirrors do not necessary mean that the collimator is perfect. Very precise alignment of these two-collimator mirrors is required to obtain the maximal theoretically possible performance. Next, precise, zero thermal-expansion optical and mechanical elements must be used in collimator design. Practically, this means that information about mirror accuracy gives precise information about mirrors performance but not about overall collimator performance. Practically, increasing accuracy of the collimating mirror not always increases the collimator performance but always increases the collimator cost.

The most typical situation is that manufacturers claim that the collimator is diffraction limited [6–8]. However, let us look at the diffraction limited target frequency values for typical collimators presented by one of the manufacturers [9] that are shown in Table 1.

Table 1. Diffraction limited target frequency values (in cycles/mrad) for collimators of different optical apertures.

	Aperture				
Wavelength	100 mm	150 mm	200 mm	250 mm	300 mm
5 μm	4.1	6.1	8.2	10.2	12.3
12 μm	1.7	2.6	3.4	4.3	5.1

As it can be seen in Table 1, the values of diffraction limited target frequencies are low, even actually very low. Table 1 suggests that resolution of typical collimators (aperture below 250 mm) during the tests of long wavelength thermal imagers is below 5 mrad^{-1} due to a diffraction limit of the collimator. This means that using such collimators for projection images of targets of frequencies over 5 mrad^{-1} we should always get blurred images of these targets generated by the tested LW thermal imagers even if the thermal imager is perfect because the collimator is the limiting factor. It is not true as the author of this paper tested LW thermal imagers and he has observed sharp images of the targets of frequency over 10 mrad^{-1}, clearly over the suggested diffraction limit of the collimators.

There are two reasons for this situation. First, the formula that was used by the manufacturer [9] to calculate the values of the limited target frequency v_{max} is too pessimistic, $v_{\max}(1/mrad) = D(cm)/2 \times 0.244\,\lambda(\mu m)$. Second, an aperture of the tested imagers is always smaller than the aperture of the collimator. This means that quality of the image generated by the optics of the tested thermal imager is degraded by both aberration blur and the diffraction blur but quality of the image projected by the collimator is degraded only by its aberration blur.

To summarize, diffraction blur should not be used as criterion of collimators quality. It is a misleading parameter. Next, both mirror accuracy and aberration blur of the main off-axis mirror can be treated as indicators of possible collimator quality. However, they are not the parameters that would give warranty about quality of collimator at the user hands. The IR collimators should be characterized using a parameter called spatial resolution that depends on aberration blur and this parameter should be measured at the final user facilities.

3. Review of criterions on IR collimators

There have been published some general guidelines for spatial resolution of IR collimators used for testing of thermal imaging systems.

First, that the collimator influence on the image obtained on the imager's screen should be negligible [1]. It is generally accepted in optical community that influence of one optical block onto the final image is negligible when spatial resolution is ten times better than spatial resolution of the second block. However, thermal imaging system as a non-typical optical system consists of optical, detection, electronic and visualisation blocks. It means that its spatial resolution cannot be determined using definitions of spatial resolution of a typical optical block which represents IR collimator and the mentioned above rule cannot be used to determine requirements on IR collimator for testing thermal imagers.

Second, more precise guideline can be found in Refs. 2 and 3 where it is stated that the collimator aberrations should be significantly less than the aberrations of the system under the test. It was suggested that this condition is generally fulfilled when a collimator focal length is at least five times that of the system under the test. This condition is quite precise and easy to use. However, validity of this condition is based on two assumptions.

First, that the aperture aberrations are inversely proportional to F-number, or powers of the F-number of optical system. It is generally true but an off-axis aberration depends on other parameters like an angle of view or aperture obscuration factor, too. Therefore, the higher F-number does not always mean lower aberrations.

Second, that spatial resolution of thermal imaging systems is limited mostly by its optics. It means that to have negligible influence of collimator on final thermal image, collimator spatial resolution must be many times better than the optics spatial resolution. However, this assumption is not usually fulfilled. Optics is often the best block from the point of influence on the final image degradation. Therefore it is possible to have a situation when aberrations of the collimator are the same as aberrations of the system optics but still collimator influence on final image degradation is negligible.

As it was shown, the mentioned earlier assumptions are often not fulfilled and we can meet situation when the condition on relationship between the focal length of IR collimator and the focal length of the tested system, proposed in Refs. 2 and 3, is fulfilled but image degradation caused by the collimator is not negligible or vice versa. Therefore this condition can be only used as a general guideline for design of IR collimator for testing thermal imaging systems.

A precise condition on the spatial resolution of the IR collimator for testing of thermal imagers was presented in Ref. 4

$$\beta \leq 0.53\omega, \tag{1}$$

where β is the spatial resolution of the collimator (angular blur diameter of the collimator) and ω is the imaging resolution of the thermal imager to be tested.

The condition can be used if only a spatial resolution of the thermal imager and spatial resolution of the IR collimator are known. However, practically it is difficult to use this condition to evaluate collimators to be used for testing the modern thermal imagers because it is difficult to get information about values of the spatial resolution of the collimator and the spatial resolution of the tested thermal imager.

If we want to know the spatial resolution of the collimator, we must practically measure aberration blur of the collimator because the manufacturers rarely publish such data. If we want to know spatial resolution of the thermal imager, then we should carry out measurement of slit response function (the resolution ω was defined as a slit dimension for which slit response function is equal to 0.5). Spatial resolution based on SRF was the most popular way to characterize resolution of the first and second generation of thermal imagers (particularly commercial thermal imagers) but nowadays SRF data is rarely published.

To conclude, we can say that a new evaluation method of IR collimators for testing modern thermal imagers is needed. The optimal situation would be if the condition on spatial resolution of the IR collimators could be verified using low cost apparatus that are easily commercially available. Now, let us develop an evaluation method that fulfils this requirement.

4. Evaluation method

In order to develop a method that could enable evaluation of IR collimators for testing thermal imaging systems we should:

- find a way to measure spatial resolution of the collimator using low cost easily available apparatus,
- determine theoretical spatial resolution of the thermal imagers on the basis of typically available imager data,
- determine a condition between the collimator spatial resolution and thermal imager resolution that, if fulfilled, then collimator influence on test results of the thermal imager, is negligible.

IR collimators used for testing thermal imagers are typically reflective off-axis parabolic collimators like shown in Fig. 1. The mirrors are covered using aluminium, gold or silver coatings and are characterized by wide spectral ranges, say 0.3–15 μm in case of aluminium or silver, 0.6–15 μm in case of gold coatings. The collimators can be used not only to project images in typical spectral range of thermal imagers, 3–5 μm or 8–12 μm but also in the visible range 0.38–0.78 μm. In case of a collimator with gold coating, its ability to project images is limited to the part of the visible range 0.6–0.78 μm but still such a collimator can be used to project visible images.

Next, aberrations of reflective collimators do not depend on the spectral range. Further on, transmittance of reflective collimators with silver or gold coatings almost do not depend on a wavelength. Transmittance of reflective collimators with aluminium coatings depends significantly on a wavelength, it is better in far infrared than in visible range.

The situation described above makes it possible to carry out measurement of spatial resolution due to aberrations in visible range. We can be sure that the results of the visible range tests should be equal to the far infrared range tests.

Let us replace the blackbody and IR targets shown in Fig. 1 on a visible source and typical visible targets as shown in Fig. 2. Then, the collimator will project visible images that can be evaluated by human sight. Let us use a standard USAF 1951 resolution target for such tests (Fig. 3). Human eye cannot be directly used to evaluate

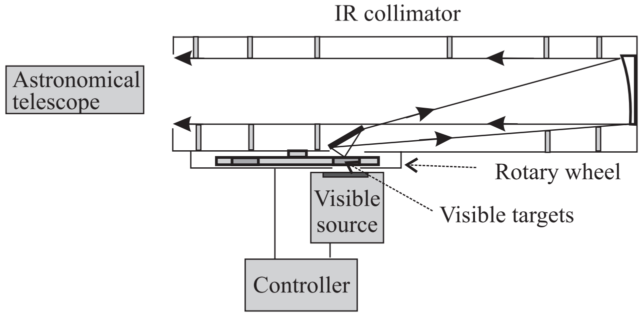

Fig. 2. Block diagram of a system for evaluation of IR collimators.

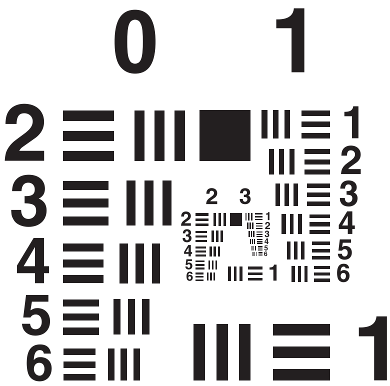

Fig. 3. The USAF 1951 target to be used for collimators testing.

quality of images projected by the collimator due to its too low resolution. However, if supported using a high magnification astronomical telescope then human eye can be transformed into precise tool for evaluation of IR collimator quality.

Using the laboratory set-up presented in Fig. 2 we can carry out measurement of the spatial resolution v_{co} of the IR collimator calculated as

$$v_{col}(mrad^{-1}) = \frac{v_{usaf}(mm^{-1})}{f'(m)} \tag{2}$$

where v_{usaf} is the frequency of the smallest bar target the observer is able to recognize and f' is the collimator focal length.

Please note, that the measurement should be done only if the USAF 1951 targets is properly illuminated using a diffuse source of light. The observer should be able to regulate illumination level until he finds optimal illumination level that produces the best measurement results. In case of testing IR collimators with gold coating, it is recommended to insert an orange filter into the optical channel in order to compensate for the limited spectral transmittance of gold in visible range. In this simple way we can measure spatial resolution of the collimator that can be treated as reliable indicator of collimator quality. Now, let us find what should be a relationship between collimator spatial resolution and resolution of the tested thermal imager.

There are many definitions of spatial resolution of thermal imagers [10]. Let us choose a resolution defined as the Nyquist frequency v_N. This parameter determines a thermal imager theoretical limit and what is also important it can be easily determined on typical data offered by manufacturers. The spatial resolution v_N defined as Nyquist frequency of the thermal imager can be calculated as

$$v_N(mrad^{-1}) = \frac{N}{2 \cdot FOV(mrad)}, \tag{3}$$

where N is the number of pixels in horizontal (or vertical) direction of FPA used in imager design, FOV is an imager field of view in horizontal (or vertical) direction.

It is commonly accepted in optical community of visible range that influence of a collimator on degradation of final image generated by the tested optical system can be treated as negligible when collimator spatial resolution is at least 5 times better than spatial resolution of a tested system. Let us apply the same rule to testing of thermal imagers. It leads us to a conclusion that, to have collimator influence on degradation of image generated by tested thermal imager negligible, the collimator resolution v_{col} must be at least 5 times better than thermal imager resolution v_N

$$v_{col} \geq 5v_N. \tag{4}$$

However, we must remember that the spatial resolution v_{col} is a measured value using a technique that generates results always worse that true collimator resolution in a situation when v_N is the theoretical imager resolution.

Resolution of modern reflective collimators it is typically at least 50 mrad^{-1} [11]. Resolution of semi-professional telescopes is usually over 400 mrad^{-1} what is almost 10 times better than collimator resolution [13]. It means that in case of semi-professional telescopes, the influence of telescope quality of a measurement result is negligible and Eq. (4) is fully valid. However, resolution of amateur telescopes is typically below ~200 mrad^{-1} [12]. This means that telescope resolution is no better than four times over collimator resolution. Therefore we can expect that measurement results of collimator resolution using typical amateur astronomical telescopes will be about 25% worse that true collimator resolution. Therefore let us take into account this decrease in resolution measurement result and modify Eq. (4) into a more fair form for the collimators

$$v_{col} \geq 4v_N. \tag{5}$$

To summarize, it is recommended to use high quality telescopes of resolution over 400 mrad^{-1} during measurement of collimator resolution. If such telescopes are used, the collimator quality should be evaluated using Eq. (4). If low cost amateur telescopes were used during tests of the collimator, the collimator quality should be evaluated using Eq. (5). However, this case is not recommended, we will assume that that high quality telescopes were used and Eq. (4) is to be used for further investigations.

Equation (4) gives us precise, easy to use condition on spatial resolution of IR collimators for testing thermal imagers. The collimator resolution v_{col} can be easily measured and thermal imager resolution can be easily determined on typically available basic imager data. In this situation, Eq. (4) can be easily applied to any IR collimator by the users of test systems to check if their collimator can be used for testing thermal imagers.

5. Discussion

Let us chose a few commercially available thermal imagers and calculate a minimal spatial resolution of IR collimators using Eqs. (3) and (4) values. In this way, we will be able to formulate precise requirements on IR collimators to be used in equipment for testing modern thermal imagers. The calculation results are shown in Table 2. We can make a few conclusions from the data presented in this table.

First, the requirements on spatial resolution of IR collimators significantly depend on a field of the tested thermal imagers. The requirements are very low in case of imagers working in a wide field of view mode but they are many times higher in case of the same imagers working in a narrow field of view mode.

Second, IR collimators of spatial resolution higher than 70 mrad^{-1} can be used for testing all thermal imagers available on the market. If we exclude from the analysis the case of a long range imager of a very narrow field of view and 640×480 resolution FPA, then we can say that collimators of the resolution at 50 mrad^{-1} are acceptable. If long range thermal imagers of a very narrow field of view are not tested, then even the collimators of the resolution at 25 mrad^{-1} can be considered as acceptable.

Table 3. Parameters of the tested thermal imager.

FOV (HFOV×VFOV)	FPA	v_N (mrad^{-1}) (horizontal)	Required v_{col} (mrad^{-1})
NFOV: 0.98×0.71 (17.1×12.4 mrad)	320×240	9.36	46.8

6. Experiments

In order to validate the condition of Eq. (4), an experiment was carried out. A long range cooled thermal imager of a very narrow field of view of the parameters shown in Table 4 was used during the experiment. As we can see in Table 4, the imager was characterised by extremely good resolution and testing such imagers creates high requirements on the collimator in the test system.

During the experiment, MRTD characteristics of the thermal imager were measured using two methods. First, MRTD was measured using a classical variable target test system (commercially available DT 2500 test system [11]) of configuration shown in Fig. 1. Next, MRTD was measured using a variable distance test system of a configuration shown in Fig. 4 (commercially available the LAFT test system [11]). The first test system was built using an IR collimator of resolution equal to 46 mrad^{-1}. It is almost exactly the resolution needed to fulfil the condition of Eq. (4) when we want to test the thermal imager of the parameters shown in Table 4. The second test system did not use a collimator to project images. Therefore we can expect that the difference between the results generated by both test systems should be caused by possible degradation of the projected image by the IR collimator and that the results

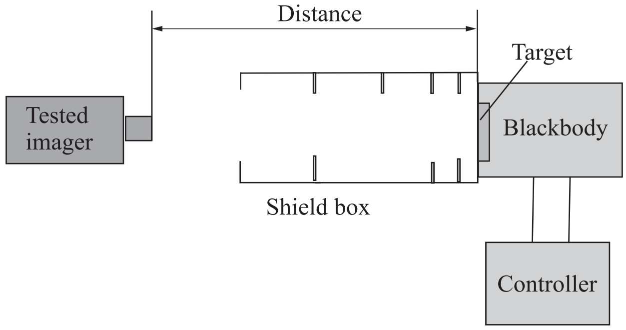

Fig. 4. Block diagram of variable distance test system used for experiment (LAFT test system [11]).

Table 2. Requirements on the spatial resolution v_{col} of IR collimators to be used in testing different thermal imagers.

Thermal imager	FOV (HFOV×VFOV)	FPA	v_N (mrad^{-1}) (horizontal)	Required v_{col} (mrad^{-1})
Elvir (Thales Angenieux)	FOV: 8×6 (140×105 mrad)	320×240	1.14	5.7
Thermovision 2000 (FLIR)	WFOV: 25×18 (436×314 mrad)	320×240	0.37	1.85
	MFOV: 6×4.32 (105×75.3 mrad)		1.52	7.6
	NFOV: 0.98×0.71 (17.1×12.4 mrad)		9.36	46.8
Matiz long range SAGEM	WFOV: 6.53×4 (114×69.8 mrad)	640×480 (equivalent microscanning)	2.8	14
	NFOV: 1.36×0.91 (23.7×15.9 mrad)		13.5	67.5
Ultra 275C FLIR	WFOV: 18×13 (314×227 mrad)	320×240	0.5	2.5
	NFOV: 4×2.89 (69.8×50.4 mrad)		4.6	23

HFOV– horizontal field of view
VFOV – vertical field of view

from the second test system should be better if the degradation of image quality by the collimator is significant.

The distance between the target and the imager during MRTD measurements, using the first test system, was very short (almost equal to focal length of the collimator – 2.5 m). However, the collimator projected image of the target to the tested imager as a long distance target located at optical infinity. The second test system was equipped with a large size 4-bar pattern target (bar width equal to 15 mm). Because of large target dimensions, the distance test system – the imager during MRTD measurement was longer than in case of the first test system. The distance varied from 60 to 300 m and was longer than the imager minimal focusing distance. Therefore in both versions of the test systems, we can assume that imager optics was working under the proper focusing conditions.

The results of the described earlier comparison tests are shown in Fig. 5. As we can see in this figure, there are some differences between the results of MRTD measurements received using two different measuring test systems. The results get using the collimator based test system are slightly worse that the results get using the non-collimator test system at high frequency range. However, the difference is small and becomes negligible close to the Nyquist frequency. In a situation when the dispersion of the measurement results, during MRTD measurement at 20% level, is typical even at the laboratory conditions, then we can conclude differences between the test results get using two different test systems are negligible. Because one of the system was designed using a collimator in a situation when the other test system was built without the collimator we can conclude that the influence of the IR collimator that fulfils the condition of Eq. (4) on the measurement results is negligible. This means that when a collimator fulfils the condition of Eq. (4) then it can be used for image projection in the systems for testing thermal imagers.

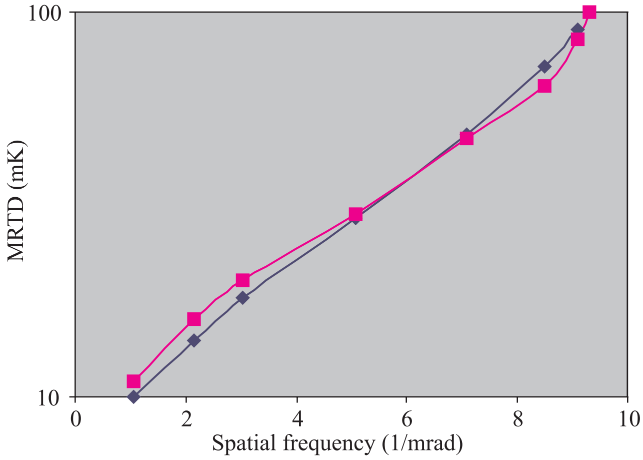

Fig. 5. Results of the comparison tests (triangle – results from the collimator based test system – DT 2500 system, squares – results from the direct viewing test system – LAFT test system).

7. Conclusions

This paper provides international specialists, involved in testing thermal imagers, two tools for optimisation and verification of infrared reflective collimators.

First, the condition on collimator performance derived in this paper can be used to prepare optimal requirements on the collimators to be used in test systems.

Second, the method for evaluation of IR collimators to be used for testing thermal imagers presented in this paper enables us practical verification of any IR collimator at the final user facilities without any information from its manufacturer, only basic data about thermal imager to be tested is required.

Using these two tools, the users of infrared reflective collimators can minimize purchase costs of new collimators by setting the optimal requirements or verify performance of the collimators they have in their laboratories.

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