CDT

Off–axis reflective collimators

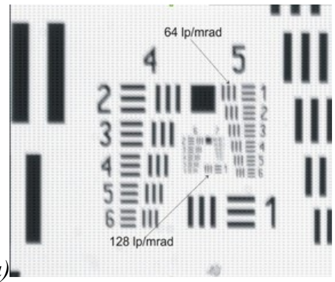
Fig. 1. Photos of three CDT collimators

a)

b)

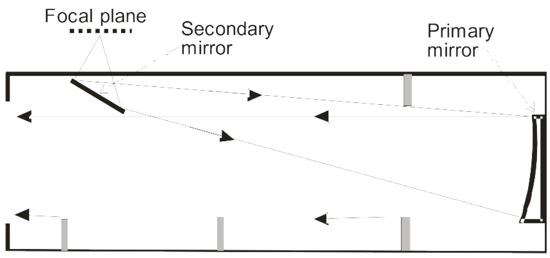
c)

Fig. 2. Photos of three test systems built using three collimators (long black tubes) of different aperture and focal length.



a)

Fig. 3. Photo of an USAF 1951 target projected by a collimator.



b)

Fig. 4. Block diagram of off–axis reflective collimator.

1 Basic information

According to classic definition collimators are optical devices for producing (collimating) a parallel beam of rays. Practically, collimators are typically used not to produce collimated beam of rays but as optical systems that project image of a target located in "optical infinity" (very long distance) (Fig. 3).

Off–axis reflective collimators are dominant type of collimators used in systems for testing electro–optical imaging systems. They are collimators that use a collimating mirror made from non–central part of a bigger paraboloid (Fig. 4). Additional flat mirror to rotate optical axis is commonly used too. Off–axis reflective collimators dominate market of system for testing EO imagers due to three advantages:

1. Very wide spectral band due to lack of chromatic aberration,
2. Ability to project close to perfect image (negligible aberrations) of a target located at/near collimator focal point,
3. More affordable than refractive collimators, in case of medium/large collimators of aperture over about 100mm),

4. Unobstructed aperture, compared to reflective on–axis collimators (off–axis collimators offer of the primary collimating mirror because the secondary mirror is located outside collimator output aperture).

Inframet manufactures a long series of off–axis reflective collimators (coded CDT collimators) of different aperture, and focal length/size (long black tubes at Fig. 2) to be used in different systems for testing EO imagers. This data sheet give detail information on off–axis collimators manufactured by Inframet.

2 Technical challenges

In spite of this simple optical structure, manufacturing high performance off–axis reflective collimators is a technical challenge, particularly in case of collimators of large optical apertures (over 300mm) due to several reasons.

First, typical optical elements are symmetric and technology of manufacturing of such optics has been mastered during last hundred of years. However, off–axis parabolic mirrors are asymmetric elements and manufacturing large off–axis parabolic mirrors with high accuracy (deviations from theoretical parabolic surface must be fractions of wavelength of visible light) is challenging.

Second, high accuracy mirrors are typically manufactured using grinding and polishing method. It is a very time consuming method in case of large mirrors. Several months are needed for manufacturing large (over 300mm) off–axis reflective mirrors.

Third, perfect quality of image projected by collimator can be achieved only in case of perfect alignment: target is exactly at collimator focus. However, determination of focus position with a high degree of accuracy is a difficult task.

Fourth, precise alignment of collimator mechanical axis with collimator optical axis is needed to project image at proper direction.

3 Mirror manufacturing technologies

There are two main types of off–axis parabolic mirrors due to different manufacturing technologies:

1. Mirrors from glass blanks processed to the off–axis paraboloid shape using grinding and polishing methods.
2. Mirrors from metal blanks (aluminum, copper, nickel, or cupronickel) processed to the off–axis paraboloid shape using diamond turning. Sometimes additional polishing is used.

Classic technology to manufacture glass mirrors is costly and time consuming but enables potentially to manufacture high accuracy mirrors. Newer technology to manufacture metal mirrors using diamond turning is much cheaper and faster. However, it is not possible to achieve high accuracy level, especially in case of medium size or bigger mirrors (diameter over 100–150mm). Due to these reasons metal mirrors are rarely used in off–axis collimators with exception of collimators of small apertures. Metal off–axis parabolic mirrors are available on mass market at low cost but are poorly suited for use in image projectors, particularly in visible/near infrared range. Manufacturing accuracy of best metal mirrors is several times lower than accuracy of classical glass mirrors.

Inframet does not use metal mirrors at all and uses only glass made mirror. There are three main types of glass that are used in fabrication high perfermance mirrors: low–expansion borosilicate glass (LEBG), synthetic fused silica and Zerodur.

Low–expansion borosilicate glass (LEBG) known under a series of commercial brand names (Pyrex, Borofloat, Supremax) is mass produced glass that offers low coefficient of thermal expansion and can be easily polished to high accuracy. It is well suited for high quality front–surface mirrors designed for low optical deformation when working at moderate temperature range. Synthetic fused silica has a very low coefficient of thermal expansion. Fused silica mirrors can be polished to extreme accuracy, thereby minimizing wavefront distortion and scattering. Zerodur is a unique glass–ceramic material whose thermal expansion is almost zero. This stability is essential in diffraction limited systems where the optical figure must not vary under thermal changes.

Inframet typically uses mirrors from borosilicate glass. Mirrors from synthetic fused silica or from Zerodur are used only for collimators to work at extreme temperature conditions or to manufacture ultra high accuracy performance collimators.

Metallic coatings are typically used as reflective coatings of the mirrors to improve their reflectivity. Spectral range of the reflective collimators is determined by coatings of the mirrors. There are three types of most often used metallic coatings: aluminum, silver and gold. All three types of coatings offer similar high reflectivity over about 95% in the spectral range of interest: 1–15 µm but differ in performance in visible&near infrared range 0.4-1 µm. Next, all these coatings need some kind of dielectric overcoat that arrests the oxidation process or to improve its mechanical properties.

Gold offers consistently very high reflectance (about 99%) from about 0.8 µm to about 50 µm. Silver offers slightly lower reflectance (about 97%), but broader spectrum from 0.3 µm to over 20 µm. Aluminum coatings are characterized by lower average reflectivity (about 96%) at wavelengths over 2 µm and a certain reflectivity drop in visible and more in near infrared. The advantages of aluminum coatings are very good durability and the lowest costs. Additionally, reflectance of aluminum coatings increases with a wavelength. Practically, there is only a slight difference in 3-15 µm spectral region between aluminum mirrors or gold mirrors in case of collimating mirrors, where a mirror surface is nearly perpendicular to the incoming beam. This difference increases in case of secondary flat mirror working at about 45 deg angle.

4 Collimator versus test system

Collimator is the most important block of systems for testing electro–optical imaging system. Its task is to project image of a reference target located at collimator focal plane (typically one of targets fixed to rotary wheel) into direction of tested EO imager. Due to its importance sometimes the term "collimator" refers to complete test system (collimator, radiation source, rotary wheel with targets – see Fig. 4) but such terminology is improper. Inframet treats the term collimator as important, but only one of many blocks of system for testing EO imaging/laser systems.

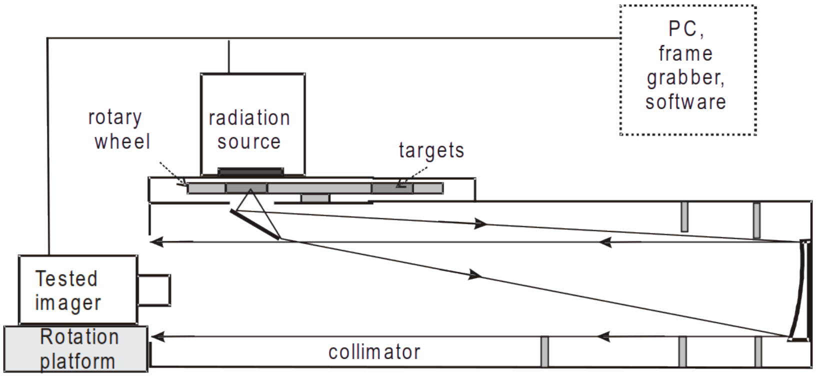


Fig. 5. Block diagram of typical system for testing EO imagers

In addition, it should be remembered that collimator alone is an expensive, but practically useless block. It needs to cooperate with other blocks (at least target located at collimator focal plane) for any practical use.

5 Commercial offer

Inframet typically sells its collimators as part of bigger test systems (long series of different systems for testing thermal imagers, VIS–NIR cameras, SWIR imagers, laser systems, fused systems and multi sensor systems). However, Inframet can optionally sell also collimators for customers who have already other blocks of EO test systems or built a new customized EO test system.

Potential customers are expected to deliver detail description of application of the collimator and design of test system to be built. The reason is that Inframet has had negative cases of complaints of customer about collimator quality when the real reason was poor aligning collimator/target/radiation source or non optimal choice of collimator version.

6 Collimator configuration

Inframet typically manufactures off–axis reflective collimators for work in so called vertical configuration. Collimator focal plane is over collimator mirrors in vertical configuration (Fig. 7). If the collimator is used in systems for testing thermal imagers, then the rotary wheel is put on the collimator (in collimator focal plane). Next, radiation source is located above the rotary wheel with targets.

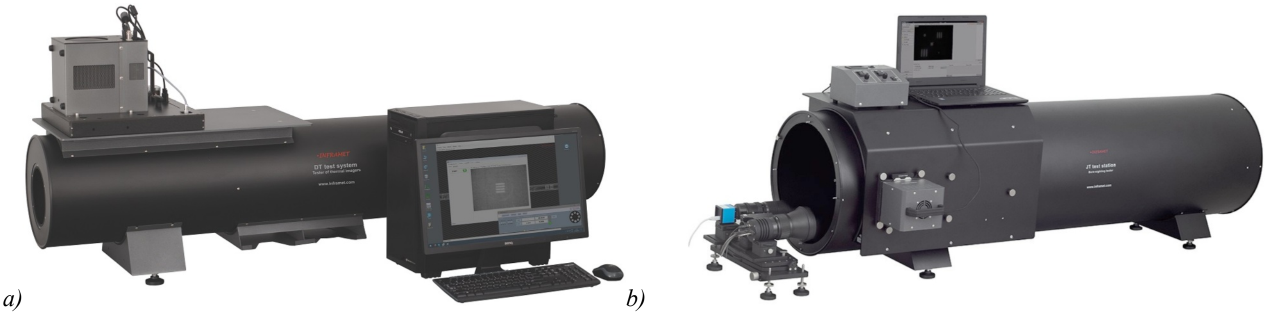


Fig. 6. Test systems based on collimator in two configurations: a) vertical (MRW rotary wheel, targets and TCB blackbody are on the collimator top plate) b) horizontal (collimator top plate is used only as a small table for laptop and controler)

This type of collimators enables design of compact test systems (only small narrow table is needed). There is also a more important advantage of collimators in vertical configuration. System for testing thermal imagers built using vertical configuration collimators offers better blackbody temperature uniformity than system built from the same modules in horizontal configuration. This difference in performance is caused by smaller air fluctuation in vertical configuration test systems (more details in K. Chrzanowski, Li Xian–min, Configuration of systems for testing thermal imagers, Optica Applicata, Vol. 40, 4, 2010).

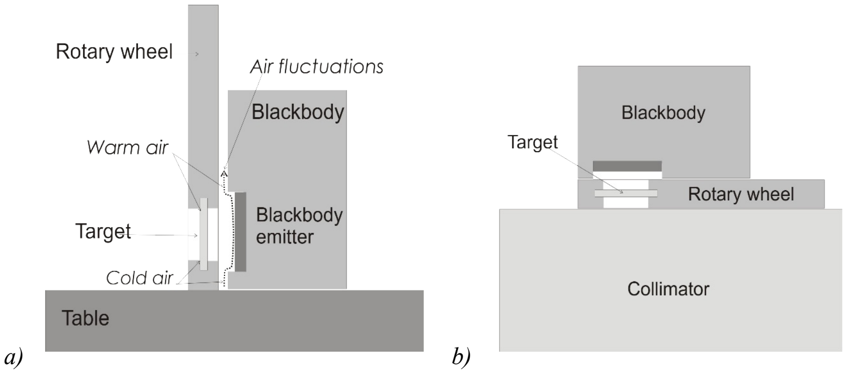


Fig. 7. The blackbody, the rotary wheel and the targets of the test system a)horizontal configuration, b)vertical configuration

Vertical configuration collimators are also recommended due to compactness of test systems built using such collimators for any applications. However, it should be noted that Inframet can also deliver collimators in horizontal configuration with focal point at the same height as collimator axis. This configuration enables design of more flexible test systems where all blocks are located on an optical table. Changing from vertical to horizontal collimator configuration is technically a rotation by 90º of the main cylindrical block. However, Inframet should be informed what configuration is preferred when order is sent.

7 Characterization of off–axis collimators

Off axis reflective collimators can be characterized by a set of parameters/features:

1. aperture
2. focal length
3. FOV
4. F–number
5. transmission
6. image quality (different parameters)
7. range of simulated distance (focus range)
8. accuracy of simulated infinity distance
9. work temperature

7.1 Collimator aperture

Collimator aperture of well designed collimator equals to diameter of output hole in collimator body. The latter hole equals to diameter of active part of off–axis parabolic mirror. This parameter determines maximal input pupil of optical objective of imager that can be tested. It is recommended that collimator aperture must be over 10% larger that aperture of optics of tested imager.

7.2 Collimator focal length

In detail, there are two focal lengths of off–axis collimators:

1. slant focal length SFL that equals the distance between mechanical center of off–axis parabola mirror and parabola focus (Fig. 8),
2. effective focal length EFL that equals the distance between center of parent off–axis parabola mirror and parabola focus.

EFL describes optical properties of collimator and is presented in collimator data sheet. Anyway, the difference between SFL and EFL is minimal (typically below 0.5%). A series of collimator parameters like collimator size, FOV, or image quality depends on collimator focal length. The most obvious is relation with collimator size. The rule is that collimator with longer focal length is bigger. FOV is inversely proportional to collimator focal length. Relationship focal length and image quality is presented in F–number section.

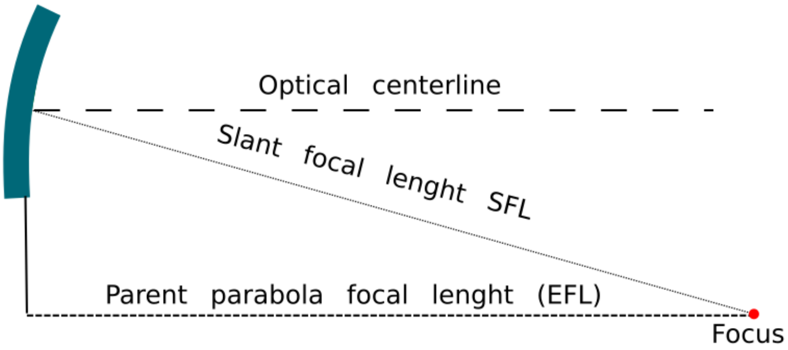


Fig. 8. Optical parameters of off–axis parabolic mirror

7.3 Collimator FOV

Collimator nominal FOV precisely should be defined as maximal angular size of image projected at collimator output. In other words nominal FOV equals to angular size of maximal target located at collimator focal plane and seen by tested imager. This parameter depends mostly on properties of collimating mirror (off–axis distance, focal length), size of secondary mirror, and diameter of input hole in collimator body.

Practically the effective FOV is typically smaller comparing to the nominal FOV because maximal size of a target that can be projected is actually limited by diameter of holes of rotary wheel located at the collimator focal plane. The holes in the rotary wheel determine maximum size of the target that can be projected by the collimator. Therefore, Inframet calculates FOV of manufactured collimators as a ratio of diameter of holes in rotary wheel to collimator focal length (in mrad).

Many potential users of reflective off–axis collimators can project a perfect image only of a target located at the center of collimator FOV (near collimator focus). Quality of the projected image quickly deteriorate with a distance from the center. This is a theoretical limitation of off–axis parabolic reflective collimators not related to manufacturing imperfections. Therefore, the FOV of off–axis reflective collimators offered on the market (including Inframet collimators) is rather narrow, typically not higher than 3º. In case of collimators of large aperture (over or equal 400mm) FOV can be even below 1º.

Collimators of wider FOV are needed for testing short range imagers having low Nyquist spatial frequency. Collimators of narrow FOV are acceptable for testing long range range imagers with high Nyquist spatial frequency. In both cases the rule is that collimator FOV must be big enough to overlap biggest resolution pattern (resolution target) needed for tests. The second rule is that it is typically acceptable when collimator FOV is only a part (as low ten times smaller) of FOV of tested imager. The only exception is situation when tested EO imager works only in automatic gain control (example: night vision devices based on image intensifier tube) and the collimator FOV must be comparable or bigger than FOV of tested imager.

7.4 Collimator F–number

Collimator F–number is defined as a ratio of the collimator focal length to the collimator aperture. F–number of off–axis reflective collimators offered on the market vary from about 4 to about 12.

Big advantage of low F–number collimators (bright collimators) is small size of such collimators due to shorter focal length. In addition, shorter focal length of such collimators enables also to achieve the same FOV using smaller targets/radiation source comparing high F–number collimators (dark collimators).

Both types of collimators offer the same image quality of targets located at center of collimator FOV. However, image quality of non center targets is much worse in case of bright collimators (Fig. 9). Therefore, Inframet recommends dark collimators (F–number in range 8–10) in spite of bigger size and necessity to use bigger targets and radiation sources. For this reason, Inframet systems often generate slighly better results of resolution, MTF, MRC, MRTD comparing to typical test systems based on bright collimators.

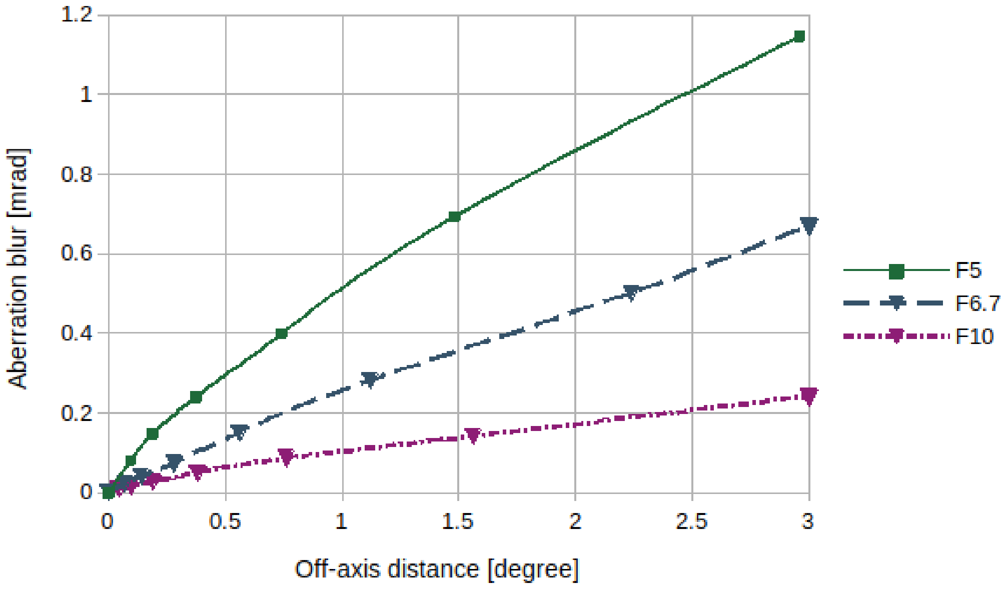


Fig. 9. Aberration blur versus off–axis distance for several reflective off–axis collimators of 150mm aperture and different F–number[1].

Further on, if multi-pattern resolution targets are top be used for testing high resolution imagers then it is recommended to keep smallest patterns in center part of the target (near focus of the collimator) because collimator performance is the best for on axis point. It is common error to locate small patterns at off axis positions.

7.5 Collimator transmission

Inframet typically uses protected aluminum as a coating for both mirrors. If higher transmission in both visible and near infrared spectrum is needed, then protected silver coating is used for the secondary flat mirror or both mirrors. Solutions in form of two mirrors coated using protected silver or protected gold are also possible. As we see in Table 1 transmittance of reflective collimators can be increased by using silver coating or gold coatings. However, it should be remembered that silver coating is more vulnerable to humid climate or industrial pollution than typical aluminum coating. Next, gold offers excellent durability but at cost of drastically lower transmittance at visible spectral band. It is also soft and it is later risky to clean mirrors coated using protected gold.
It should be noted that values in Table 1 refer to transmission of complete (two mirror) collimator. Sometimes requirements on reflectance of single mirror are presented in tender specifications.

Table 1 Transmission of reflective collimators built using mirrors with different coatings

No	Coating	Transmission				
		VIS	NIR	SWIR	MWIR	LWIR
1	Both mirrors – protected aluminum	0.79	0.76	0.86	0.92	0.93
2	Primary mirror – Protected aluminum; Secondary mirror – protected silver	0.84	0.84	0.9	0.93	0.93
3	Both mirrors – protected silver	0.93	0.93	0.93	0.93	0.93
4	Both mirrors – protected gold	0.36	0.96	0.96	0.96	0.96

Attention: These are average values.

7.6 Collimator image quality

Characterization/testing off–axis collimators is not standardized. However, it can be said that there are four main

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[1] Aberration blur was calculated as an angular diameter of a rectangle detector getting 71% energy of a ideal point source.

methods to characterize/test off–axis parabolic mirrors (example values in Table 2):

1. Manufacturing accuracy of off–axis parabolic mirror
2. Collimator front–wave error
3. Collimator resolution
4. Modulation Transfer Function.

The first method is based on an idea that quality of image projected by the collimator can be well estimated by manufacturing accuracy of the collimating mirror. The assumption is a relatively sound: collimating mirror is the main limiting factor for overall accuracy of the collimator. High manufacturing accuracy of the collimating mirror is the necessary condition to design perfect coordinator. However it is still possible to design a poor collimator even when using perfect collimating mirror. Therefore Inframet typically presents information about mirror manufacturing accuracy in collimators documentation, but adds also some additional parameters.

Front wave error of a collimator is a deviation from ideal wavefront (flat or spherical) when projecting image of a point source. It is typically measured at 0.63um light spectrum and expressed in numbers that refer to:

1. max deviation (peak to volley),
2. rms value of deviations (Table 2).

Front wave error appears to be a very good indicator of collimator quality. It is based on similar logic as used to characterize accuracy of optical elements for at least a century. Wavefront error of optical systems like collimators can be measured using a long series of methods: Shark–Hartman wave front sensor, scanning cube corner retro–reflector, shearing interferometry, Talbot interferometry, Lau interferometry, modified Michelson interferometry and so on. However, practically there are several important drawbacks of wavefront error criterion of collimator quality.

First, there is no direct clear relationship between parameters that characterize quality of image generated by EO imagers (to be tested) and wavefront error of collimator. Such a situation makes difficult for collimator users to estimate what wavefront error is truly needed to enable accurate testing of EO imagers.

Second, it is relatively easy to measure wavefront error of small collimators (aperture below 100mm) but difficult to test collimators of aperture over about 300mm. Wavefront error meters are extremely expensive. Users of systems for testing EO systems typically do not have wavefront error measuring stations and are not capable to verify image quality of delivered off–axis collimators.

Third, front wave is typically used to characterize image quality in center of collimator FOV. No information of collimator performance in full FOV

Due to these reasons Inframet has technical capabilities to measure wavefront errors of collimators but prefers two other parameters to characterize quality of image projected by collimators:

1. collimator resolution,
2. collimator MTF.

Both collimators and tested EO imagers can be characterized by measuring resolution understood as spatial frequency of smallest resolution patter that can be resolved in images generated by these imaging systems. It is also commonly accepted that collimator resolution should be several times higher over resolution of imager to be tested to keep negligible influence of collimator on test results. In detail, in ideal case it is recommended that collimator resolution is to be over five times higher than imager resolution.

Resolution of collimators of apertures up to about 300mm can be relatively easy measured using high grade astronomical telescopes. These telescopes are affordable for many customers of EO test systems who can use them to verify performance of off–axis collimators. Therefore Inframet presents information about resolution in data sheet of manufactured collimators or complete test systems. In fact Inframet divides manufactured collimators onto four grades (SR, HR, UR, XR) depending on measured resolution (details in next section).

Collimator resolution gives information about collimator performance at high frequency range when in real work more important is performance at low frequency range. Information about performance in the latter range can be delivered by collimator MTF function after comparing to MTF of tested EO imager. Therefore MTF in Inframet opinion is the best parameter to characterize quality of images projected by collimators. However, measurement of MTF is more difficult comparing to resolution tests. Therefore, Inframet offers information on MTF of its collimators only as an option.

Table 2. Results of tests of exemplary CDT collimator using four methods

No	Parameter	Exemplary value
1	Manufacturing accuracy of collimator mirrors	L/10 P–V at 630nm or L/70 RMS at 630nm
2	Collimator front–wave error	L/3 P–V at 630nm or L/22 RMS at 630nm
3	Collimator resolution	at least 320 lp/mrad
4	MTF	at least 0.4 at 80 lp/mrad

It is commonly accepted that requirements on quality of image projected by collimator (collimator grade) are determined by resolution of tested imager. However, resolution of EO imagers of the same optics aperture can vary a lot. Resolution of LWIR imager can be twelve times lower comparing to resolution of VIS–NIR camera built using optics of the same aperture. Further on, requirement on collimator are much higher in case of testing single big long range EO imager comparing to testing multi–sensor system built using several small short/medium range imagers. The conclusion is that requirements on quality of image projected by the collimator vary a lot and there is little sense to deliver perfectly aligned collimator built using perfectly manufactured mirrors for testing imagers of low resolution. Therefore, Inframet manufactures collimators divided into four grades depending on two criteria:

1. mirror manufacturing accuracy,
2. collimator resolution.

Mirror manufacturing accuracy gives information on maximum deviation of surface of collimator mirrors relative to ideal paraboloid or ideal flat. It should be noted that mirrors of higher manufacturing accuracy can potentially generate high quality images only if used in properly aligned collimators. Therefore, SR/HR/UR/XR symbols determine not only mirror manufacturing accuracy, but also the class of aligning of the collimator, and thermal stability of collimator body. It should be also noted that even the worst mirrors coded as SR class are so called diffraction limited in MWIR/LWIR range.

Manufacturing accuracy of UR/XR grade mirrors is precisely measured using interferometric methods and detail measurement data is delivered to customer. Manufacturing accuracy of SR/HR grade mirrors is estimated using classical Foucault knife/edge method (optionally measurement of MTF). Collimator resolution is measured as a spatial frequency of minimal resolvable 3–bar pattern of an image of USAF1951 target projected by the tested collimator. The target is located at the collimator focal plane and is illuminated using quasi monochromatic 630nm light source. Measurement is done using a reference near perfect astronomical telescope

There is always some degradation of perceived image due to imperfection of the measuring tool (astronomical telescope). Therefore, the measured resolution is always smaller comparing to true resolution. This difference is especially strong for best XR grade collimators. However such a situation is safe for customer that gets better collimator than suggested by measured resolution. Precise rules for division of CDT collimators into four grades: SR, HR, UR and XR are presented in Table 3. To qualify for higher grade, the collimator must fulfill both conditions.

Table 3. Criterion of grade division of CDT collimators

Collimator grade	SR	HR	UR	XR
Manufacturing accuracy (P–V at 630nm)	$<\lambda/2$	$<\lambda/4$	$<\lambda/8$	$<\lambda/12$
Collimator resolution*	>0.2x TR or >70 lp/mrad	>0.4 x TR or >180 lp/mrad	>0.63x TR or >280 lp/mrad	>0.85x TR or >490 lp/mrad

* – whatever smaller

Theoretical resolution TR according to Rayleigh criterion can be calculated as below:

$$TR[lp/mrad]=\frac{D[mm]}{1.22\,\lambda[um]} \quad ,$$

where D is collimator aperture, and λ is wavelength of light source equal to 0.53um (center of visible band). Precise values of required minimal resolution of collimators of different aperture/grade are presented in table 4.

Table 4. Minimal resolution of collimators of different grade

aperture [mm]	Grade			
	SR	HR	UR	XR
40	12	25	39	53
60	19	37	58	79
80	25	49	78	105
100	31	62	97	131
120	37	74	117	158
150	46	93	146	197
200	62	124	195	263
250	70	155	244	329
300	70	180	280	394
350	70	180	280	460
400	70	180	280	490
500	x	180	280	490
600	x	180	280	490

7.7 Range of simulated distance

Apparent distance to target simulated by collimator projecting image of such a target depends on location of target plate relative to collimator focal plane. This distance equals infinity if the target is located exactly at collimator focal plane. Collimator shall simulate target located at real finite distances if distance target–collimating mirror is shorter than collimator focal length.

EO imagers are typically tested at lab conditions using collimator test systems that project images of target located at optical infinity. Such situation is typically totally acceptable because typical distance imager–target at field conditions is over a thousand times higher that focal length of optics of such imagers. Such distance can be considered as near infinity because image quality of target generated by imager does not changes when distance is changed from work distance to true infinity. Therefore there is typically there is no need for collimator simulating non–infinity distances to simulated target. However, there are several exceptions from this rules.

First, simulation of non infinity distance is needed simulate influence of real work conditions (extreme temperature, vacuum conditions) on image generated by tested EO imager. Second, it is necessary to verify performance of focusing mechanism of optical objective. Such faulty mechanism can generate noticeable image shift even for minor focusing and generate important boresight error.

In such a situation Inframet typically offers its CDT collimators integrated with MRW rotary wheels with targets located precisely at collimator focal plane. Test system built in this can simulate targets only at one distance: optical infinity.

However, Inframet offers also another solution: FRW focusing rotary wheel. This is a special rotary wheel that combines rotation with linear movement along collimator optical axis (movement range at least 20mm). This solution enables continuous regulation of distance to simulated target. Minimal simulated distance depends on focal length of the collimator and is presented in Table 5.

Table 5. Minimal simulated distance for collimators of different focal lengths

Collimator focal length [cm]	100	120	150	160	200	240	300	350	400	500	600
Minimal distance [m]	50	75	100	125	200	300	400	600	800	1200	1800

7.8 Infinity tolerance

Ideal collimator projects image of a target located at infinity distance because the target is fixed perfectly at collimator focal plane. However, in real life there is always infinity focus error (distance between target plane and focal plane of the collimator). This error can vary from zero to about one millimeter depending mostly on collimator grade and use of focusing tools (Table 6).

Table 6. Infinity focus error for CDT collimators of different grade (SR/HR/UR/XR) with different focusing/target exchange tools

	Tool for precision focusing/target exchange	SR	HR	UR	XR
Infinity focus error at customer site*	No precision focusing (MRW wheel)	±0.8 mm	±0.4 mm	±0.3mm	±0.2mm
	Precision focusing – Yes (FRW wheel)		±0.3 mm	±0.2mm (option: ±0.1mm**)	±0.15mm (option: ±0.05mm**)

* – after typical transport conditions and working at laboratory conditions

** – after optional collimator realignment by Inframet engineer at customer site using Infimet focusing checker.

Infinity focus errors of CDT collimators presented in Table 6 can appear significant but are practically negligible for great majority of EO imagers due to a number of reasons. First, relative focusing errors are extremely low (below 0.1%) because collimators of long focal length (over 1m) are typically used. Therefore, such refocusing cause only very minor change of collimator optical power (below 0.001D). Second, when testing typical focusable imagers (thermal imagers, VNIR cameras, SWIR imagers) used in Earth conditions it does not matter if the test system simulates targets at optical infinity or 10km because tested camera can refocus to get best image. Third, majority of non focusable imagers use optics of low focal length and are non sensitive even to big infinity focus error.

The only case of EO imagers that can be potentially sensitive to infinity focus errors of test collimator are non focusable space imager of narrow FOV built using optics of long focal length comparable to collimator focal length. For such a case Inframet offers special service of our engineer at customer site to measure and correct position of focus after long distance transport.

Anyway, the general rule is that imager sensitivity to collimator focusing error is proportional to ratio of imager focal length to collimator focal length. Therefore, it is recommended to use collimators of long focal length when testing space imager even if they generate problems due to large size (large optical tables and large clean room are needed).

7.9 Ambient temperature

Variable ambient temperature can cause some degradation of performance of off–axis reflective collimators. In detail, there are three main effects of degradation:

1. defocus (change of simulated distance),
2. degradation of quality of projected image,
3. angular shift of collimator axis (shift of projected image).

Typical CDT collimators manufactured by Inframet are optimized to work in maintenance/repair workshops of thermal imagers in ambient temperature range from about +10ºC to about +30ºC. The negative effects listed above are negligible when working at typical work conditions, especially when used at laboratory condition, that is ambient temperature varies in range 22ºC±2ºC. Inframet can also optionally deliver special athermal collimators optimized for work at extreme temperatures from about –30ºC to about +70ºC. In detail, Inframet manufactures collimators of three levels of athermalization:

AT0 – collimators at basic version that can work only at typical temperature range from about +10ºC to about +30ºC,

AT1 – collimators can work at extreme temperature range from about –30ºC to about +70ºC with negligible deterioration of image quality but noticeable defocusing and image angular shift can occur.

AT2 – collimators can work at extreme temperature range from about –30ºC to about +70ºC with negligible deterioration of image quality, defocusing and image angular shift.

AT0 class collimators are typical Inframet offer; AT1/AT2 collimators are optional offer.

8 Versions of CDT collimators

Inframet offers a long series of CDT collimators of different aperture, focal length, FOV, image quality (resolution) optimized to work with different rotary wheel using target plates of different size (Table 7).

Attention: Collimator FOV and target size have been calculated for case when collimator cooperates with Inframet rotary wheels.

Table 7. List of models of collimators offered by Inframet

CDT collimator model	**Aperture [cm]**	**Focal length [cm]**	**Linear FOV (target size)[mm]**	**Angular FOV [º]**

660–44	6	60	44	4.19
1050–35	10	50	35	4.00
1080–44	10	80	44	3.15
11100–44	11	100	44	2.47
12100–44	12	100	44	2.47
15120–44	15	120	44	2.06
15150–44	15	150	44	1.65
20160–44	20	160	44	1.54
20200–75	20	200	75	2.11
25200–44	25	200	44	1.24
25200–75	25	200	75	2.11
30200–44	30	200	44	1.24
30200–75	30	200	75	2.11
30300–44	30	300	44	0.82
30300–75	30	300	75	1.40
35200–44	35	200	44	1.24
35200–75	35	200	75	2.11
35350–75	35	350	75	1.20
40240–75	40	240	75	1.76
40240–44	40	240	44	1.03
40400–75	40	400	75	1.05
45500–107	45	500	107	1.20
50300–75	50	300	75	1.40
50500–75	50	500	75	0.84
60600–107	60	600	107	1.00

Collimators listed in table above can be deliver in four different image quality grades (SR, HR, UR, XR). Collimator code is composed from four parts:

1. aperture in centimeters,
2. focal length in centimeters,
3. linear FOV in millimeters,
4. grade.

Example: CDT20160–44–UR means collimator of following features:
aperture = 20cm, focal length =160cm, linear FOV=44mm, grade=UR.

9 Options

As can be seen in previous section CDT collimators are offered in many versions. Here we shall present additional optional solutions.

Options:

1. Platform for target exchange/focusing:
   1. No (customer is expected to deliver it),
   2. MRW rotary wheel,
   3. FRW focusing/rotary wheel,
2. Mirror coating:
   1. both mirrors – protected aluminum,
   2. Primary mirror – Protected aluminum; Secondary mirror – protected silver,
   3. both mirrors – protected silver,
   4. both mirrors – protected gold (details in Table 1),
3. Athermalization (details as in Section 7.9):
   1. athermalization at AT0 level (typical temperature range 10°C –30°C,
   2. athermalization at AT1 level,
   3. athermalization at AT2 level,
4. Configuration (details as in Section 6):
   1. Vertical,
   2. Horizontal.

Customer is expected to fill table below if these options (solutions no 2–3) are interested. Solutions no 1 is part of basic versions discussed in previous section.

Table 8. Example set of options

No	Option name	Value
1	Platform for target exchange/focusing	FRW focusing/rotary wheel
2	Mirrors coating	both mirrors ALU
3	Athermalization	AT0
4	Configuration	Vertical

It recommended to keep basic option as more advanced options generate price increase when are typically not needed. The exception from this rule is option no 1: Platform for target exchange/focusing. The cheapest solution is not to order any such platform and use simple manual wheel with targets made at hoc by customer. However, the risk is that customer will not be able to achieve required precision positioning and output image quality shall be poor. Options when Inframet delivers its own platforms (especially focusing rotary wheel FRW) eliminates such possibility.

10 INFRAMET quality control

Inframet carries out two stages of quality control of CDT off–axis reflective collimators:

1. Tests of collimator mirrors:
    1. off–axis parabolic mirror,
    2. flat mirror.
2. Tests of complete collimator at Inframet facilities,
3. Tests of complete collimator at customer facilities.

Two methods are used to test off–axis parabolic mirrors:

1. Fizeau Type Interferometer method for testing mirrors of class UR/XR,
2. Calibrated Foucault knife method for testing mirrors of class SR/HR. Flat mirrors are tested using interferometry plate method.

Official certificates of quality of off–axis parabolic mirrors are delivered in case of UR/XR mirrors.

Complete collimators are tested in standard way by measurement of collimator resolution using 100% contrast USAF195 target. Cost of such test service is included in collimator price. Inframet can also carry out additional tests of quality of images projected by collimator using two new methods: 1)measurement of collimator front wave, 2)measurement of modulation transfer function MTF of the collimator. For technical details see Section 7.6. Measurement of front wave or MTF are optional paid test services.

Performance of CDT collimators do not deteriorate in noticeable way after typical shipment of these optical systems in special boxes that protect collimator against vibration or mechanical shocks. In addition, collimator resolution is typically many times higher comparing to resolution of tested EO imager and minor deterioration of quality of image projected by collimator has no influence on test results. Therefore, additional tests of collimators at customer facilities are typically not carried out.

Inframet can offer optional paid tests of CDT collimator. Four different types of tests are offered:

1. Low contrast resolution
2. Infinity focus,
3. Collimator MTF,
4. Wavefront test.

First, simplified collimator test by measurement of low contrast resolution. In detail, image of low contrast (10%) USAF1951 target is projected by the collimator and is visually analysed using high grade astronomical telescope. It is required that measured low contrast resolution is higher over maximal Nyquist frequency of imager to be tested. Such result confirms that collimator influence on image quality of targets used in tests of EO imagers is negligible. Second, position of collimator focus (infinity focus) is measured and corrected is needed. Tests are carried out using special Inframet focus checking tool coded Infimet. Third, collimator MTF is measured using test set delivered by Inframet (expanded version of Infimet tool). Fourth, wavefront of CDT collimator is measured using Inframet wavefront test station transported to customer facilities. All these four tests are optional paid tests. The first method is cheapest and recommended for any collimators. The methods 2–4 are recommended only for case of testing of space imagers of Nyquist frequency over about 100 lp/mrad (XR grade collimators).

11 How to choose optimal collimator?

Resolution of tested EO imagers can be estimated as equal to imager Nyquist spatial frequency of such imagers. In detail, Nyquist spatial frequency determines maximal spatial frequency (smallest sinusoidal bar patterns) that imager can reproduce perfectly. Nyquist spatial frequency of tested imagers can be easily calculated in two ways:

1. ratio of imager focal length to (in mm) to dimension of pair pixels of image sensor used by the imager (in μm),
2. half of ratio of pixel number (unitless) of image sensor to imager FOV (in mrad unit). Nyquist frequency can be also calculated as 0.5 of ratio of number of pixels of image sensor to imager FOV [mrad].

Both methods produce identical results. It is commonly accepted that resolution of collimator should be higher than resolution of tested imager. Therefore data from Table 4 gives opportunity to determine what can be maximal resolution of tested imagers tested using collimators of different aperture/grade.

However, there is no agreement on required ratio of collimator resolution to imager resolution. Some literature sources recommends to have such ratio equal five [1] when some books on testing NVDs suggest that collimator having resolution two times higher over resolution of tested imager is sufficient [2]. In addition, it is not clear that how to accommodate influence of measuring tool on measured resolution. This influence is significant in case of high grade large aperture collimators.

In such a situation Inframet proposes a simple method to choose collimator grade depending on maximal Nyquist spatial frequency of tested imagers based on company practical experience that is presented in Table 9.

Table 9. Rules to choose optimal collimator grades depending on maximal Nyquist frequency of tested imagers

Nyquist frequency of tested imagers [lp/mrad]	<5	<25	<100	<300 (option <500)
Recommended collimator grade	SR	HR	UR	XR

The numerical rules in Table 9 can be converted to following text recommendations:

- SR grade collimators: only for testing small short range imagers
- HR grade collimators: for testing short/medium/long range imagers
- UR grade collimators: for testing long/very long range imagers
- XR grade collimators: for testing space imagers of narrow FOV.

It should be noted that Nyquist frequency in Table 9 is imager frequency in lp/mrad (line pair per mrad unit). It is not image sensor Nyquist frequency in lp/mm unit.

eferences:

1. Chrzanowski, Krzysztof. "Evaluation of infrared collimators for testing thermal imaging systems." Opto–Electronics Review 15.2 (2007): 82–87.
2. J. Mackovska, “Methods of control of night vision devices”, Telekom, Moscow, 2003 (in Russian)

12 Summary

Inframet is word leader in field of off–axis reflective collimators for systems for testing EO imaging/laser systems due to a series of reasons.

1. Long series of versions of CDT collimators that differ in aperture, focal length, FOV and image quality. A set of additional options (platform for target exchange/focusing, mirrors coating, athermalization, configuration) is also offered. This numerous offer enables to optimize Inframet offer (design/cost) for customer real needs. In addition, all these collimator are offered at competitive prices.
2. Expanded data sheet of CDT reflective off–axis collimators. Customer can learn details of collimator design, performance, test methods and then make decision about possible purchase of the collimator.
3. Detail information on its quality control methods used by Inframet. Some of these methods can be optionally used at customer facilities if needed.
4. Inframet presents real measurement data (resolution) of its collimators instead of common declaration that collimator is diffraction limited (even poor quality collimators can be diffraction limited at longer wavelengths.
5. All CDT collimators are equipped with internal baffles and coated using paint of ultra low reflectance. This solution enables to eliminate unwanted reflected radiation inside collimators.
6. Long life time of CDT collimators. This parameter depends on environmental conditions but typically life time of CDT collimators is in range of 10 to 25 years (without recoating).
7. Inframet CDT collimators are typically offered in vertical collimators that enables to achieve better

thermal stability of blackbodies used when testing thermal imagers.

8. Optional thermal design resistible to ambient temperature changes. The collimator can be used in a wide range of ambient temperatures. Typical range is from +10ºC to +30ºC but can be extended.

To summarize, Inframet CDT collimators offers high ration of collimator performance to price. These collimators sold as part of bigger test systems or as stand alone block are used in hundreds of laboratories worldwide.

Version 7.3

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