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Testing surveillance thermal imagers under simulated real work conditions

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Abstract

Thermal imagers often work in extreme conditions but are typically tested under laboratory conditions. This paper presents the concept, design rules, experimental verification, and example applications of a new system able to carry out measurements of performance parameters of thermal imagers working under precisely simulated real working conditions. High accuracy of simulation has been achieved by enabling regulation of two critical parameters that define working conditions of thermal imagers: imager ambient temperature and background temperature of target of interest. The use of the new test system in the evaluation process of surveillance thermal imagers can bring about a revolution in thermal imaging metrology by allowing thermal imagers to be evaluated under simulated, real working conditions.

1. Introduction

Thermal imagers are generally divided into two basic groups: surveillance imagers and measurement imagers. The surveillance imagers are mostly used in military applications to enable observation of a battlefield in darkness and/or difficult atmospheric conditions by creating the relative temperature distribution of the terrestrial scenery being observed. The measurement imagers are used for civilian applications in industry and science, mostly for non-contact measurements of temperature distributions on the surface of the tested objects. The surveillance imagers are the dominant group of thermal imagers offered on the international market and this paper concentrates on this group of thermal imagers.

Surveillance thermal imagers are typically tested under laboratory conditions, when both imager ambient temperature and background temperature of the target of interest are equal to about 20 °C in situation when in real life these two temperatures can vary in the range from about −40° C up to about +70 °C. This shockingly high difference between laboratory test conditions and real working conditions makes it difficult, or even impossible, to precisely evaluate the effectiveness of thermal imagers working in extreme conditions based on tests made under laboratory conditions.

In order to partially solve this problem, manufacturers of surveillance thermal imagers often carry out environmental tests of these imagers according to the requirements of the popular MIL-810-STD military standard [1]. The tests are typically done by subjecting the imager located in a temperature chamber to a set of extreme ambient temperatures for a specified period of time, and checking later if there is a negligible performance deterioration due to the environmental tests compared to the performance tests conducted prior to the environmental tests. Information about such tests can be often found in data sheets of surveillance thermal imagers [2–5]. However, results of such environmental tests according to the MIL-810-STD standard give precise information only about the imager ability to survive a certain period of time at extreme ambient temperatures without a substantial performance loss after the test is finished. These tests do not give information on real performance of the tested imager when working under extreme working conditions.

Despite the limitations, the MIL tests are very popular. There are many test laboratories that offer services of environmental tests of thermal imagers according to

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MIL-810-STD military standard [6–9]. However, there is no laboratory that can offer commercial services in form of performance tests of surveillance thermal imagers by the measurement of well-known performance parameters (minimum resolvable temperature difference – MRTD, modulation transfer function – MTF, noise equivalent temperature difference – NETD) when the imager is working under extreme conditions.

Many scientific papers have been published devoted at least partially to the subject of performance tests of thermal imagers working at extreme ambient temperatures [10–13]. However, only one of these scientific papers is devoted to the subject of testing surveillance thermal imagers at temperature chamber [13]. Other papers discuss performance tests of the measurement thermal imagers used in civilian applications.

What is even more important, none of the manufacturers of the equipment for testing thermal imagers [14–17] offer commercially available mature, mass-produced systems to carry out testing of surveillance thermal imagers under extreme conditions.

The situation described above could suggest an almost total lack of interest from the scientific/industrial community in the problem of expanded testing of surveillance (mostly military) thermal imagers working under extreme conditions. However, this quite logical conclusion is not fully justified.

Based on the author's experience as CEO of one of the manufacturers of equipment for testing thermal imagers, it can be stated that there have been at least a dozen attempts worldwide to develop well-performing test systems based on the old design concepts presented in Ref. 13. However, these projects have failed to deliver well-performing test systems that could be later commercialised. Additionally, there are technical limitations to such test systems built using the concepts from Ref. 13. These test systems are only able to simulate a situation when ambient temperature is approximately equal to the background temperature.

This paper presents the test system capable of carrying out performance tests (measuring performance parameters like MRTD, MTF, NETD) of surveillance thermal imagers under realistically simulated, real working conditions. Both main parameters that characterise working conditions (1 – T_{amb}, 2 – T_{back}) can be independently adjusted. This new test system is a good fit to expectations of many scientific/industrial centres working in the field of thermal imaging. Nowadays there is a growing interest in ability to carry out not classical MIL-810-STD tests, but true performance tests of thermal imagers at extreme temperatures. The reason for this is the market situation, where there are many thermal imagers that can survive MIL-810-STD tests, but only very few can operate at extreme ambient temperatures, with only negligible deterioration in performance compared to laboratory conditions.

2. Real working conditions of thermal imagers

The range of effective surveillance (range of detection, recognition, identification of the target of interest) using a thermal imager depends on a set of five parameters: target differential temperature, target size, atmospheric transmission, imager ambient temperature, target background temperature. Since the atmospheric transmission generates the effect of decreasing the target differential temperature, it can be omitted from the list.

Influence of the target size and target differential temperature on thermal imagers performance is commonly known and can be easily tested under laboratory conditions.

This is not the case for the imager ambient tempera-ture (T_{amb}) and the target background temperature (T_{back}). The T_{amb} is precisely the temperature of the imager case. However, it can be typically assumed that the T_{amb} is approximately equal to the temperature of the air around the imager, unless there is a strong direct sun irradiation of the imager.

The T_{back} is the apparent temperature of targets that form the background of the target of interest that is perceived by an imager looking at these targets. The perceived temperature of the background can differ from the real temperature of the background due to influence of atmosphere on the perceived temperature. Detailed analysis of the relationship between effective background temperature and real background temperature is beyond the scope of this paper. For simplicity, it will be assumed that the effective background temperature is approximately equal to the real background temperature.

Now let us define typical ranges of these two parameters. Both temperatures vary a lot depending on geographical region, time of year, time, imager, and the angular configuration of the imager-target system. Definitions of the first four parameters are commonly known. The latter term needs clarification. This term defines the angle of the imager line of sight relative to the horizontal axis (difference between altitude of the imager and altitude of the target of interest). In a nutshell, it can be said that there are three main angular configurations: 1) horizontal, 2) slanted down, 3) slanted up (Fig. 1).

The first angular configuration is the most typical case. It is a typical scenario for thermal imagers used in land/navy/air applications to enable observation of land/navy/air targets located at the same altitude. For this case, the T_{amb} is approximately equal to the T_{back}. Both temperatures can vary a lot but are approximately almost the same.

The second configuration occurs mostly in case of surveillance of ground/sea targets using thermal imagers located on airborne platforms (aircraft, helicopters). The T_{amb} is typically much lower compared to the T_{back}. The difference can vary from about 5 °C to about 40 °C depending on the observation angle, distance, and weather conditions (visibility, humidity, clouds). A similar situation occurs in case of long-range imagers located on high mountains that are used for surveillance of lowland terrain.

The third configuration occurs mostly in case of surveillance of airborne targets using thermal imagers located at ground/sea level. T_{amb} is typically much higher compared to the T_{back} temperature. The difference between both temperatures can vary in the same range as in case of previous configuration.

As can be seen in Table 1, there are at least a dozen of main working scenarios (distinct combinations of two variables: T_{amb} and T_{back}) when typical tests under laboratory conditions simulate only one of such scenarios. The second conclusion is that both T_{amb} and T_{back} can vary a lot from −40 °C to +70° C. This is a shockingly wide

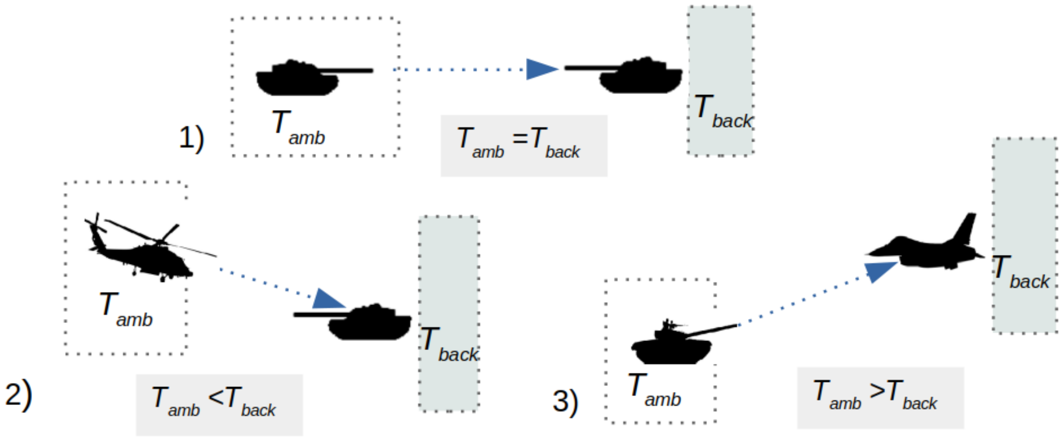

Fig. 1. Angular configurations for thermal imaging.

temperature range, but these numbers are correct. Night temperatures in the extreme winter period in polar area can drop as low as −40 °C (or below). Thermal imagers working during the day in the extremely hot summer desert conditions and under direct sun irradiation can heat up +70 °C. The same is with temperature of background targets under the latter conditions.

In such situation, it is clear that a full evaluation of thermal imagers performance should be carried out not by tests under laboratory conditions (scenario no. 1), but by measurements of performance parameters of thermal imager working under all scenarios listed in Table 1.

3. Reasons for performance changes under variable work conditions

The conclusions from the previous section suggest that potentially time-consuming measurements of performance parameters of thermal imagers under many different working conditions are needed to evaluate true performance of thermal imagers because laboratory conditions are only one of many working scenarios. However, this conclusion can be justified only if thermal imagers performance truly changes with both T_{amb} and T_{back}.

If design rules of thermal imagers are analysed then, it can be concluded that it is truly impossible to design a thermal imager of performance not sensitive to imager working conditions (T_{amb}, T_{back}) for the following reasons:

1. Apparent target differential temperature of the target of interest perceived by thermal imager does depend on T_{back}.
2. Refractive index of optical materials used in infrared (IR) optical objectives depends on T_{amb}.
3. Optical elements change slightly their shape with variable ambient temperature due to thermal expansion phenomenon.
4. Distance between optical elements changes slightly with a variable ambient temperature due to thermal expansion phenomenon of the mount material.
5. Spatial noise of thermal imagers significantly depends on both temperature of the optics/mechanical case (T_{amb}) and T_{back}.

Table 1.
Exemplary working scenarios of surveillance thermal imagers.

No.	Angular configuration	Period of the year	T_{amb}	T_{back}
1	Horizontal	Mild summer (laboratory conditions)	+20 °C	+20 °C
2	Horizontal	Mild winter	−5 °C	−5 °C
3	Horizontal	Extremely harsh winter	−40 °C	−40 °C
4	Horizontal	Extremely hot summer*	+60 °C	+70 °C
5	Slanted down	Harsh winter	−40 °C	−30 °C
6	Slanted down	Mild winter	−35 °C	−5 °C
7	Slanted down	Summer	−25 °C	+20 °C
8	Slanted down	Hot summer	−10 °C	+40 °C
9	Slanted up	Mild winter	−5 °C	−20 °C
10	Slanted up	Summer	+20 °C	−10 °C
11	Slanted up	Harsh winter	−20 °C	−40 °C

* extremely hot summer, desert conditions, direct Sun irradiation of both imager and background.

6. Transmission of some popular IR optical materials like germanium does decrease significantly at high T_{amb}.
7. Technical difficulties in designing ultra-low-noise/ultra-high-dynamic electronics needed in modern thermal imagers.

Point 1 means that the same target with a constant differential temperature relative to the background will generate a different radiometric differential signal perceived by the imager depending on T_{back}. In detail, a target of differential temperature, say, 1ºC located at a background of +40 °C will generate much stronger radiometric differential signal perceived by the imager than a target of the same differential temperature located at a background of −40 °C (Fig. 2). This means that such parameters of a thermal imager like NETD or MRTD at low spatial frequencies measured for a target at a background of −40 °C will be much worse compared to the measurement for a target at a background of +40 °C. The difference ratio is especially high for mid-wave IR (MWIR) imagers. Practically, this means that such important parameters as NETD or MRTD depend on the T_{back} due to the law of physics and this dependence cannot be corrected.

Points 2, 3, and 4 indicate the physical phenomena that create situation when quality of the image generated by infrared optical objectives significantly depends on T_{amb}. In detail, commonly known IR optics design courses teach that non-athermalized IR objectives are extremely sensitive to ambient temperature [18]. As can be seen in Fig. 3, the tolerable temperature change is too low to be accepted, especially in case of fast objectives with large aperture. Practically, this means that special, so called athermalized IR objectives should be used, if thermal imager is to be used at variable ambient temperatures.

There are three main techniques for athermalization of IR objectives: optically passive, mechanically passive, electromechanically active. The athermal objectives are supposed to be able to fully correct influence of the variable ambient temperature on the output image quality. In reality, even in case of formally athermal IR objectives, there is often some significant deterioration of image quality generated by thermal imagers while working at extreme temperatures (below about 0 °C or over about +40 °C). Some theoretically perfect objectives built with the modern aspherical technology often generate near-perfect sharp images at laboratory ambient temperatures but can generate severely blurred images when working at extreme ambient temperatures. In other words, MTF of many IR objectives working under laboratory conditions can be several times better compared to the MTF of the same objectives working under extreme conditions (Fig. 4).

Point 5 means that the spatial noise present in the images generated by thermal imagers significantly depends on the imager working conditions. Spatial noise refers to a phenomenon when a thermal imager looking at a perfectly uniform target generates an image with spatially variable brightness. The main cause of the spatial noise is spatial variability of the offset, gain, linearity of pixels of IR focal plane array (FPA) sensors. There is also some dependence of these parameters on an incoming radiometric signal.

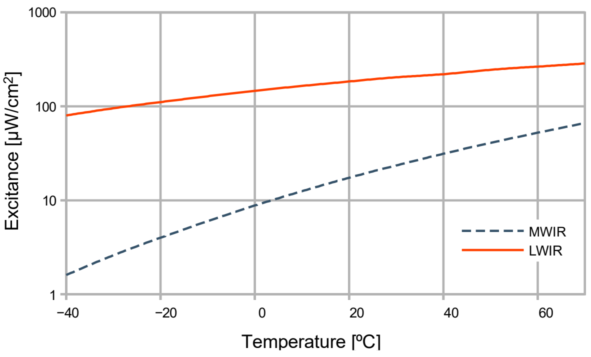

Fig. 2. Blackbody differential exitance perceived by a thermal imager looking at a blackbody with a differential temperature of 1 °C located at a background of variable temperature.

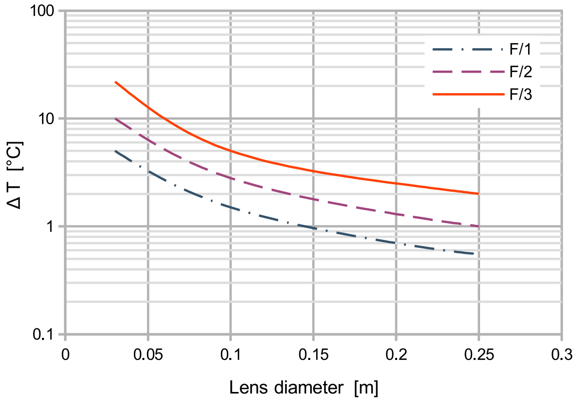

Fig. 3. Tolerable temperature change for a germanium (Ge) lens operating at 10 µm [18].

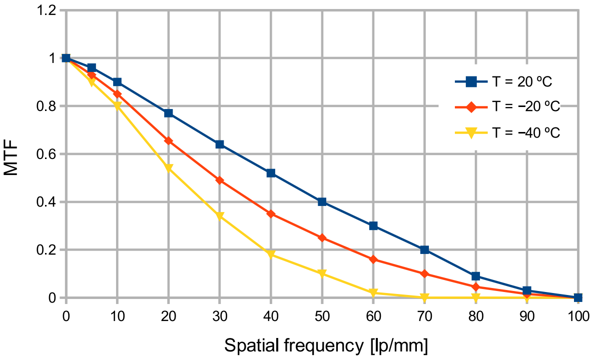

Fig. 4. MTF of an exemplary poorly athermalized 60 mm F1 long-wave infrared (LWIR) objectives working at variable ambient temperature.

Spatial noise does not depend on time, or this dependence is small. This relative temporal stability creates an opportunity to correct spatial noise of thermal images (Fig. 5). All modern thermal imagers use some algorithms to correct spatial noise. These algorithms are typically based on data from a two-point non uniformity correction (NUC) method carried out by capturing images of a large blackbody at two different temperatures (or, better, two blackbodies of different temperatures). Most thermal imagers offered on the market use a spatial noise correction algorithm based on NUC calibration carried out under laboratory conditions; only high-end thermal imagers use more advanced spatial noise correction algorithm based on NUC calibration carried out at both laboratory and extreme

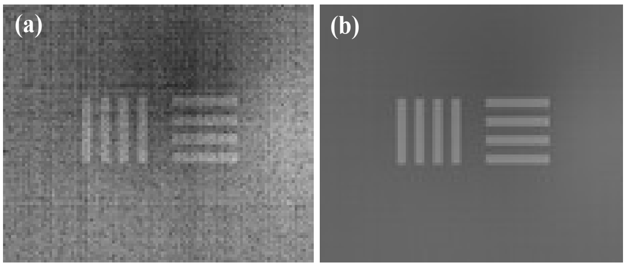

Fig. 5. Exemplary images: (a) raw image from the thermal imager and (b) image from the thermal imager after two-point NUC.

ambient temperatures (both tested imager and blackbody are in a temperature chamber). In such a situation, the spatial noise of many thermal imagers is much higher when working at extreme ambient temperatures compared to working under laboratory conditions.

Points 2–5 indicate phenomena that can be corrected, at least theoretically. However, point 6 indicates the effect that cannot be corrected: a significant increase in the absorption of the Ge lens at high ambient temperatures (Fig. 6). Transmission of an IR lens made of four 1 cm thick Ge elements can be over 30% lower at an ambient temperature of +60 °C compared to the transmission of the same lens at an ambient temperature of −40 °C. Lower transmission means a noticeable increase in the attenuation of a radiometric signal incoming to the IR FPA sensor, but what is really more important is a higher signal emitted by the optics that generates a higher spatial noise. This is a significant drawback of this popular material for IR objectives and one of the reasons for the limited performance of thermal imagers in hot desert conditions.

Point 7 indicates that many thermal imagers cannot generate clear images of targets with a low differential temperature close to their NETD for targets located at hot backgrounds (temperature over about +50 °C) due to too low dynamic range of the image processing electronics when working at high gain mode. The latter parameter is equal to the ratio of the maximum radiometric signal that can be processed by the electronic system to the rms noise of the electronic system. The maximum signal is the case when the imager looks at a target located at a hot background of the maximum temperature (typically +70 °C).

It is commonly accepted that the noise of the analogue/digital electronic systems used in thermal imagers must be several times lower than the time noise of the IR FPA sensor used by the imager. It means that the temperature difference corresponding to the electronic noise must be at least three times lower than NETD of the thermal imager. When the latter parameter can be as low as 15 mK for cooled thermal imagers, it can be concluded that the electronic noise is to be equivalent to a 5 mK temperature difference. The ratio of the radiometric signal generated by a target located at a hot background of +70 °C to the differential radiometric signal corresponding to a 5 mK temperature difference is more than 20000 times. This dynamic ratio is lower for non-cooled LWIR imagers but still is very high.

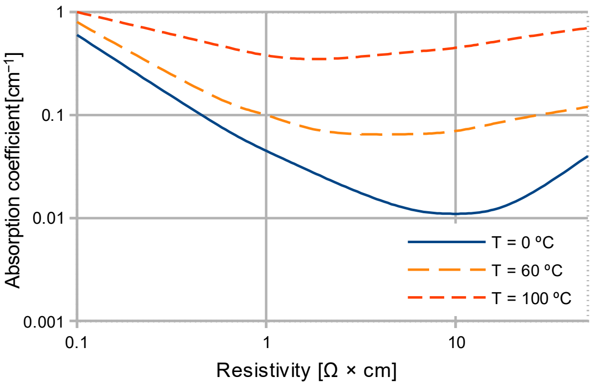

Fig. 6. Absorption *vs.* resistivity at different ambient temperatures [19].

The conclusion from data above is that if a thermal imager is to generate clear images of targets with very low differential temperature comparable to the imager NETD and located at a background of any temperature in typical working range, then a noise-free, perfect 16-bit electronic (theoretical dynamic range equals 65536) system is needed. However, practically, thermal imagers typically use 14-bit or sometimes 12-bit electronics with much lower dynamics. Manufacturers usually solve the problem of an ultra-high dynamics of the radiometric signal to be recorded by attenuation of the electronic signal for targets located at hot backgrounds. However, this solution reduces image contrast and, therefore, low-contrast targets located at hot backgrounds cannot be detected in case of many thermal imagers. There are also some thermal imagers built using simplified electronics that saturate when seeing a target located at hot background.

To summarise, it is extremely difficult to design thermal imagers capable to perform at real working conditions at the same level as under laboratory conditions. Therefore, it is natural that performance of thermal imagers offered on the market under real conditions varies a lot. There are many conflicting opinions on the performance of these imagers in a wide community of users. There are also stories of failures of these imagers in specific working scenarios. Such opinions and stories could be potentially verified by measuring some performance parameters of thermal imagers.

4. Performance parameters of surveillance thermal imagers

Militaries all over the world have always favoured the use of effective surveillance range (range of detection, recognition, identification) as the main performance criterion for surveillance thermal imagers. It is possible to directly measure detection, recognition, and identification ranges of the target of interest under field conditions and to evaluate the tested thermal camera based on such test results. However, this is a risky solution. The ranges vary with observation conditions (atmosphere, background). In addition, it is difficult to compare test results of different thermal cameras tested at different time periods and/or under different observation conditions.

Therefore, it is a typical way to evaluate thermal imagers by calculation of detection, recognition, and identification ranges of the reference target based on some parameters of thermal imagers measured under laboratory conditions. In detail, the most common way to evaluate the performance of surveillance thermal imagers is to measure

MRTD of such a thermal imager and then calculate the detection, recognition, and identification ranges to the NATO standard target using the methodology proposed by the NATO standard [20]. This standard precisely defines the parameters of a standard target, standard atmospheric conditions and shows how to calculate the detection, recognition, and identification ranges of the standard target based on the MRTD function of the thermal imager tested.

The MRTD is a subjective parameter that describes the ability of the imager-human system to detect low-contrast details of the observed object. It is a function of the minimum temperature difference between the bars of the standard 4-bar target and the background required to solve the thermal image of the bars by an observer *vs*. the spatial frequency of the target (Fig. 7). The measurement is repeated for a set of 4-bar targets of different dimensions (spatial frequency).

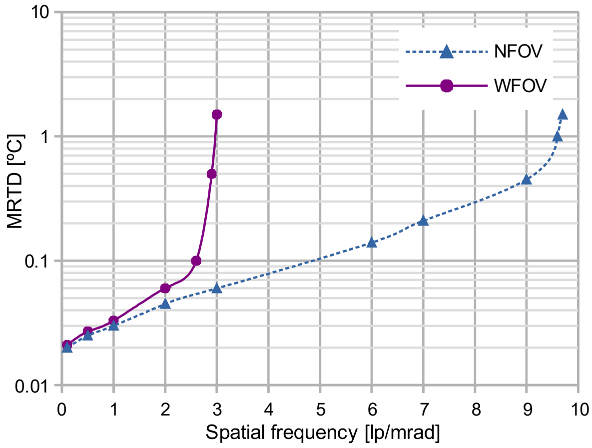

Fig. 7. MRTDs of an exemplary thermal imager with two FOVs.

There are three main methods to measure MRTD. The MRTD can be measured directly as a subjective parameter, calculated on the basis of the measured objective parameters MTF and NETD [21], or indirectly determined using a computer simulation based on the earlier listed objectives parameters [22].

MTF is a function of the contrast of the image of a sine pattern at a given spatial frequency generated by the tested camera relative to the contrast of the image of a sine pattern at spatial frequency equal to zero.

NETD can be considered as a measure of this high-frequency temporal component of the total noise. It is equal to the ratio of the standard deviation of the temporal noise of the image generated by the tested thermal imager to the signal transfer function (SiTF) of this imager.

It should be noted that all these three parameters (MRTD, MTF, NETD) are measured using reference images of a relatively low differential temperature: below 2 °C for MRTD and NETD, and below about 5 °C for MTF. Next, temperature of the background of the reference target during such measurement is approximately equal to the T_{amb} (temperature in the test room).

5. Performance tests under laboratory conditions

Performance tests of thermal imagers are typically carried out using variable target test systems built on the idea to use image projectors capable of projecting images of reference targets seen at the background of a laboratory ambient temperature. The tested imager generates copies of the projected images. Quality of the images generated by the imager is evaluated directly by human observers or by software and important characteristics of the tested imager are measured.

Test system is built from a series of blocks: off-axis reflective collimator, differential blackbody, rotary wheel, set of targets, PC set and software for controlling blackbody/wheel and for acquisition/analysis of the video image generated by the tested imager. Concept is shown in Fig. 8 and its implementation in Fig. 9.

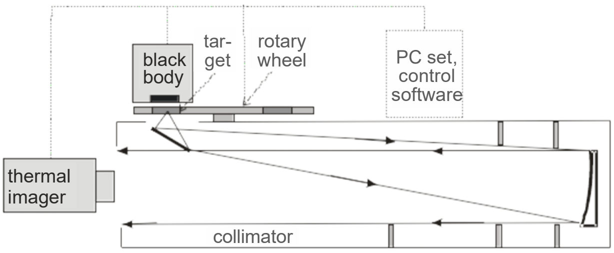

Fig. 8. Block diagram of a typical system for testing thermal imagers under laboratory conditions.

Fig. 9. Exemplary laboratory system for testing thermal imagers.

The variable target test systems project images of targets fixed to a rotary wheel using a reflective collimator as an image projector. The tested thermal imager is located at the output of the IR collimator and the target is located at the collimator input (the focal plane). The distance between the target and the tested imagers is very short (typically, approximately double focal length of collimator). However, due to the use of the collimator as an image projector, the imager "sees" the target as a faraway object that is within the imager focusing range. Next, a series of targets is fixed to the rotary wheel. By rotating the wheel, it is possible to quickly exchange targets. By changing target dimensions, the changes in the apparent distance to the target are simulated.

Off-axis reflective collimator is the critical block. High quality of images projected by the test systems can only be achieved when the collimator is built using mirrors of a high manufacturing accuracy (at a level typically not worse than P-V λ/6 at 630 nm) and properly aligned.

Influence of the working condition parameters [(T_{amb}) and T_{back}] on thermal imagers performance is commonly known. Two main computer models of thermal imagers confirm direct influence of these two temperatures on MRTD and NETD, and indirect influence on the ranges of effective surveillance of thermal imagers [23, 24].

However, despite these drawbacks, the tests of thermal imagers under laboratory conditions are commonly accepted. There are tenders for surveillance thermal imagers that require directly or indirectly the measurement of MRTD of thermal imagers carried by accredited laboratories under laboratory conditions [25–28].

Big drawback of performance tests under laboratory conditions is high probability that the results of such tests can differ significantly from the results of potential tests under real working conditions (field conditions). It should be noted that laboratory conditions (T_{amb} and T_{back} are equal to about 20 °C) represent only one of many working scenarios of thermal imagers (Table 1).

6. Tests under field conditions

A potentially easy solution to avoid drawbacks of laboratory tests is to carry out performance tests under field conditions with real targets. This solution is often favoured by authorities that make decisions on big contracts. Field tests carried out against real targets can offer a realistic performance evaluation of thermal imagers working under real working conditions. Different combinations of target differential temperature, ambient temperature and background can be simulated. However, high cost and long-time duration (sometimes it is necessary to wait for a year to be able to simulate all scenarios listed in Table 1) are big drawbacks of such tests. Further on, the measurement results (ranges of effective surveillance) vary with conditions that are difficult to control: atmospheric permeability, background temperature, and temperature uniformity.

A partial solution to eliminate these drawbacks is to carry out tests under field conditions, but against artificial targets with regulated temperature difference located at a short distance (Fig. 10). Such tests can be carried out using so called direct view test systems. Practically, such test systems are built as large area differential blackbodies integrated with a 4-bar target, wind protection hood, and electronic controller (Fig. 11), capable of stabilizing differential temperature even under field conditions (potential wind and ever-changing ambient temperature). Achieving the stable differential temperature of several mK needed for MRTD tests is a requirement difficult to meet under real field conditions. Therefore, these test systems require special protections like tents or buildings to minimize air flow and speed of ambient temperature variations. It should be also noted that direct view test systems can only offer a simulated situation where both T_{amb} and T_{back} are equal to atmospheric temperature at the time of testing. It is a very significant limitation of field testing because such potential tests represent only one of many working scenarios of thermal imagers (Table 1).

In such a situation, it can be concluded that there are significant limitations of outdoor tests and an effective accurate method to carry out tests under indoor conditions capable of simulating real working scenarios of thermal imagers shown in Table 1 is needed.

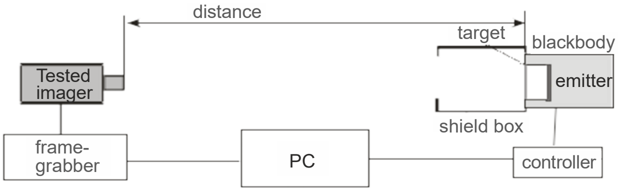

Fig. 10. Block diagram of a direct view test system for testing thermal imagers under field conditions.

Fig. 11. Exemplary direct view test system for testing thermal imagers under field conditions.

7. Typical indoor tests under simulated real working conditions

Due to the reasons listed in previous sections, it can be logically expected that there should be a common practice to carry out extensive performance tests of thermal imagers under indoor conditions capable of simulating real working conditions of thermal imagers listed in Table 1 when such tests are of a potentially critical importance for military. However, the reality is much different for several reasons.

First, it looks that this paper is the first to discuss a concept of the work of thermal imagers characterised by two independent variables: T_{amb} and T_{back}. Well-known books on testing thermal imagers always discuss the case where performance parameters measurements are made under laboratory conditions: both T_{amb} and T_{back} are equal to the typical laboratory temperature [29–32].

Second, there is no commercially available advanced test systems on the market capable to simulate all real working scenarios listed in Table 1 by enabling regulation of two independent variables mentioned in previous point.

Third, there is no commercially available mature test system on the market capable of simulating under indoor conditions the main portion of real working scenarios listed in Table 1 (horizontal configuration: T_{amb} equals T_{back}).

Fourth, there are no commercially available mature test systems capable of working at extreme ambient temperatures at temperature chambers.

The last two conclusions are surprising because there are two design concepts for building such test systems that have been known for decades [13]:

1. athermal image projector,
2. translucent temperature chamber.

Block diagrams of such test systems built using these concepts are shown in Figs. 12 and 13.

In the first case, both the image projector and the tested imager are placed in a typical non-transparent temperature

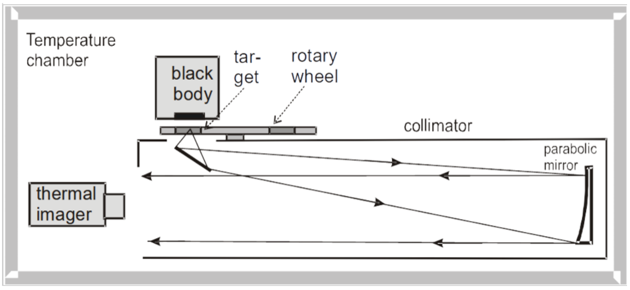

Fig. 12. Block diagram of a test system built using the athermal image projector method.

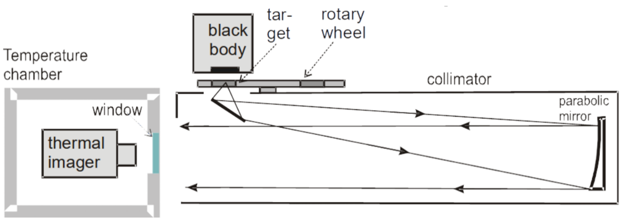

Fig. 13. Block diagram of a test system built using the translucent chamber method.

chamber. In the second case, the tested imager is placed in a translucent chamber with a transparent window and sees through this window the image projector located outside the chamber under typical laboratory conditions.

The test system based on the athermal image projector method cannot offer ability to simulate all scenarios listed in Table 1. This method can simulate both variable T_{amb} and variable T_{back} at a typical range from about −40 °C to about +70 °C. However, the important point is that simulated background temperature is always equal to simulated T_{amb}. Therefore, only horizontal working configurations (nos. 1–4 of Table 1) can be simulated accurately but these are most typical working configurations. Therefore, the athermal image projector method could be potentially a valuable tool for testing majority of thermal imagers present on the market.

There are no commercially available systems for testing thermal imagers based on this design concept on the international market. The most probable reason for such situation are technical difficulties to design the athermal image projector. It is commonly known that designing a large athermal IR objective is a technical challenge. Image projector needed for thermal imagers testing can be treated as an optical objective (reflective collimator) integrated with a blackbody, a rotary wheel. The last two are electronic blocks potentially sensitive to extreme temperatures, too. Therefore, designing athermal image projectors capable of working at a wide range of ambient temperatures from −40 °C to about +60 °C without performance loss is a big challenge.

Building a test system based on the translucent chamber method seems easy. In this case, it is apparently sufficient to make a hole in the wall of the temperature chamber, insert an IR transmitting window there, put the tested imager inside the chamber while keeping the image projector outside the chamber. This apparent easiness of testing thermal imagers in extreme conditions is multiplied by the fact that both temperature chambers and IR transmitting windows are offered on the market at large quantities at a reasonable price.

There are no commercially available translucent temperature chambers for testing thermal imagers on the market. However, the author is aware of several cases of such customized chambers developed by thermal imagers manufacturers to test their products. In some cases, designers have developed the needed chamber with a high-performance translucent window. However, the essence is a test system based on a translucent chamber, even with a perfect window that allows only the regulation of imager variable ambient temperature. The simulated background temperature is fixed and equal to the ambient temperature in the laboratory (typically about 20 °C). Therefore, only a small fraction of working scenarios (nos. 1 and 7 of Table 1) can be accurately simulated. Realism of simulating operation at extreme ambient temperatures is low. For example, such test system can simulate thermal imager working in winter conditions (T_{amb} of −40 °C) but only when the imager looks at a target located at the background of an ambient temperature of +20 °C (Fig. 14). Therefore, test results can be positive even when such imager can poorly perform against a typical target located at the background of −40 °C (typical working conditions in the extreme winter period).

Fig. 14. Low probability scenario simulated by a typical translucent chamber method: an Eskimo in Arctic (T_{amb} of −40 °C) is looking at an elephant in warm Africa (target at the T_{back} of +20 °C under laboratory conditions).

In such a situation, it can be stated that a new, more advanced system is needed for testing thermal imagers in all working scenarios listed in Table 1. In detail, the new test system should allow the regulation of two independent variables characterising the imager working conditions: T_{amb} and T_{back}.

8. New method for testing thermal imagers under variable working conditions

The concept of a new system for thermal imagers testing under variable working conditions is based on three ideas:

1. using two temperature chambers: one for a tested imager, second for an image projector,
2. both chambers should share one wall having a transparent window,
3. the image projector must be athermalized.

The new dual-chamber test system is built with three main blocks (Fig. 15):

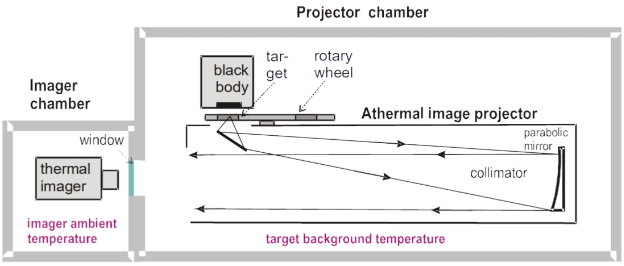

Fig. 15. Block diagram of the dual-chamber test system.

1. athermal image projector,
2. imager chamber,
3. projector chamber.

The first block – athermal image projector – is an image projector capable of projecting high quality images at any ambient temperature in the required range of −40 C to +70 °C. Performance of this block is supposed to be non-sensitive to variable ambient temperature.

The second block – imager chamber – is a small translucent temperature chamber where the tested imager is inserted.

The third block – projector chamber – is a large temperature chamber where the athermal image projector is located.

This new testing method can be treated as a fusion of two classical methods (1 – athermal image projector, 2 – translucent chamber) discussed in previous section. This fusion eliminates the main drawback of these classical methods: lack of independent regulation of both T_{amb} and T_{back}. In case of the new method, both temperatures can be regulated as independent variables in the full range from about −40 °C to about +70 °C. It means that all the scenarios listed in Table 1 can be simulated. The test system based on this new method will be called dual-chamber test system.

The T_{back} is equal to the temperature of the target plate that simulates the background of the target of interest. The target plate is mechanically connected to the rotary wheel of the test system. Therefore, the temperature of the movable target is approximately equal to the temperature of the rotary wheel where the temperature sensor is located. In such a situation, the T_{back} can be measured using the sensor placed at the rotary wheel.

Regulation of the T_{back} is achieved by changing temperature (cooling/heating) of air in the projector chamber where the image projector is placed. The regulation is done using typical cooling/heating systems commonly met in temperature chambers. However, it should be noted that it is a slow regulation due to high thermal inertia of the target plate connected to two modules of high-mass and good thermal conductivity: rotary wheel and collimator.

T_{amb} is precisely the temperature of the case and optics of the tested imager. However, over the longer period of time and in a typical situation when there is some air flow around the imager, then the T_{amb} is approximately equal to the T_{back} of the air in the imager chamber. The latter temperature can be regulated using the air temperature controllers in the imager chamber.

9. Critical requirements for dual-chamber test system

There are two main tasks of the dual-chamber system for thermal imagers testing under variable working conditions:

1. accurate measurement of main performance parameters of thermal imagers,
2. accurate measurement of boresight errors of thermal imagers.

Both measurements should be carried out under conditions that resemble real working conditions of the tested imager (combinations of two critical temperatures listed in Table 1).

There are three main performance parameters of thermal imagers that are to be measured using the dual-chamber system: MRTD, MTF, NETD. Definitions of these parameters have been presented in section 4. Measurements of these parameters under variable working conditions could enable a direct evaluation of thermal imagers working under different real working conditions.

There are three main boresight errors of thermal imagers that are to be measured: 1 – focus through, 2 – zoom through, and 3 – mechanical boresight error.

Focus error through boresight is the maximum angular deviation of the optical axis (typically line of sight) of a thermal imager when the operator focuses on the IR objectives of this imager.

Boresight zoom error is the maximum angular deviation of the optical axis (typically line of sight) of a thermal imager when the operator zooms in on the IR objectives.

Mechanical boresight error is the angular difference between its line of sight and the reference mechanical axis/plane of the tested imager. Axis of the mechanical mount (typically Picatinny mount), where the thermal imager is mounted, is typically treated as the reference axis. Some larger thermal sights use a reference mechanical plane (typically a front wall).

It should be noted that the second task (measurement of boresight errors) is actually optional. It is needed only while testing thermal sights. In case of tests of typical thermal imagers used only to generate images of the scenery of interest, boresight errors do not exist because there is no defined line of sight.

From the optical point of view, the dual-chamber system is basically an expanded image projection system (image projector with an additional transmitting window). If the dual-chamber system is to be capable of performing both discussed tasks, then this expanded image projection system must fulfil a series of requirements:

1. the image projection system is designed to survive work at extreme ambient temperatures,
2. the image projection system is to project images of reference targets of regulated shape (4-bar, edge, square), and regulated angular dimensions of projected targets (spatial frequency of projected 4-targets images),
3. target differential temperature of projected images must be regulated at least in the range from 0 °C to +10 °C;
4. target differential temperature of projected images must be regulated with a resolution of at least ten times below the lowest NETD or MRTD at the low spatial frequency range of the tested image (1 mK can be acceptable),

5. imager working conditions (T_{amb} and T_{back}) must be regulated in the range at least from −40 °C to +70 °C,
6. imager working conditions (T_{amb} and T_{back}) are to be regulated with accuracy that ensures accurate determination of its influence on measured parameters of the tested thermal imager. An accuracy of 0.1 °C can be considered as satisfactory;
7. optical aperture of collimator and optical aperture of the window must be at least 10% higher compared to the aperture of the tested thermal imager,
8. blurring of the image received by the tested imager due to the limited performance of both image projector and translucent window at any ambient temperature in both chambers must be negligible,
9. angular shift of the image received by the tested imager due to limited performance of both image projector and translucent window at any ambient temperature in any of the chambers must be negligible,
10. the image projection systems should allow for some limited regulation of the distance to a simulated target when testing thermal imagers with manual focusing only.

Points 1–6 are clear and present precision requirements in contrast to points 7–10. Point 7 presents conditional requirements that need some clarifications. In case of points 8–10, the situation is even more complicated. These are rather general guidelines that must be converted into more precision requirements.

The conclusion from point 7 is that the requirements for both collimator aperture and transmitting window aperture vary depending on the aperture of optics of the thermal imager under test. Collimators/windows with an aperture of 100 mm are satisfactory for portable thermal sights or short/medium range surveillance imagers, but collimators/windows with an aperture of up to 200 mm (or more) may be needed when testing long-range surveillance imagers.

The quality deterioration of the projected image by the image projector (collimator) is caused by four main effects:

1. defocusing due to thermal expansion of collimator metal case with variable ambient temperature,
2. defocusing due to thermal expansion of collimating mirror along collimator optical axis,
3. deviation of surface of collimating mirror from ideal parabolic shape caused by mirror thermal expansion, mechanical strains caused by mirror thermal non-uniformity, or mechanical strains caused by mirror mounting,
4. image blurring due to deviation of surface of secondary mirror from perfect flat caused by mechanical strains due to mirror thermal non-uniformity, and/or mechanical strain caused by mirror mounting.

Requirements for quality of the image projected by the image projector due to its limited performance can be presented in different ways. One of such ways is a relationship between resolution of an image projector measured at visible spectral band (influence of diffraction effect is minimal) and Nyquist frequency of the tested imager. It has been shown that influence of the collimator resolution ν_{col} (practically resolution of the image projector) on quality of the projected reference image is negligible when the collimator resolution is at least four times higher than the Nyquist frequency ν_{N} of the tested imager [33]:

$$\nu_{\mathrm{col}} \geq 4 \cdot \nu_N \,. \tag{1}$$

Thermal imagers are typically designed in a way to ensure that the Nyquist frequency of the imager is lower than 0.5 of the objective diffraction limit. The latter parameter can be calculated as ratio of the IR objective aperture D_{obj} [in mm] and the mean wavelength λ_{mean} [in μm] of the imager spectral band. The diffraction limit is higher in case of MWIR imagers (mean wavelength of 4 μm) compared to LWIR imagers (mean wavelength of 10 μm). Further on, as discussed in case of point 7.

Maximum aperture of IR objective D_{obj} [in mm] of the thermal imager should be always lower than 0.9 of the collimator aperture D_{col} as discussed in point7. Finally, on the basis of all these relationships, (1) can be converted to a new form:

$$\nu_{\mathrm{col}} \geq 0.45 \cdot D_{\mathrm{col}}\ [\mathrm{lp/mrad}]. \tag{2}$$

Image transmitted by the translucent window is sometimes degraded by deformation of surface of the plates that form such a window (deviation from ideal flat surface) due to mechanical strains generated by high temperature difference at two opposite surfaces of the window. Flatness of at least the external surfaces of the window can be measured using the interferometric Fizeau fringes method.

In case of the visible optics, it is commonly accepted that windows of flatness at level P-V λ/4 at 630 nm (P-V – peak-to-valley, λ – wavelength) are considered as high-grade precision optics that do not degrade transmitted image [34]. Mean wavelength of MWIR imagers (4 μm) is 6.35 times longer than a 0.63 μm wavelength. The same ratio is even higher in case of LWIR imagers. Therefore, requirements for flatness needed to obtain negligible degradation of the image transmitted by the IR window for the translucent chamber can be relaxed. The new form of the P-V deviation of the WF window surfaces from an ideal flat surface can be presented as below

$$\mathrm{WF} \leq 1.6\,\lambda \quad \text{when } \lambda = 630\ \mathrm{nm}. \tag{3}$$

Real requirements for variation of the angular position (requirement of point 9.) of the image projected by the image projector mostly depend on a thermal imager type. Even significant variations in the angular position of the projected image at the level of dozens of pixels are basically acceptable for surveillance thermal cameras used only for observation. However, such a situation is totally unacceptable for thermal sights or thermal imagers used in multi sensor targeting systems when the aiming mark must pinpoint the target of interest with an acceptable boresight error. However, there is still an open question what it is meant by ‘acceptable error’.

In the case of portable thermal sights, the acceptable image shift is equal to repeatability of mounting such sights on rifles. The latter parameter is typically not better than about 0.4 mrad.

The requirement of point 10 seems apparently illogical in a situation where the collimator is typically expected to simulate targets located at optical infinity. The reason for simulating targets at variable distances is related to the design of IR objectives used in thermal imagers. Great majority of IR objectives (even so-called athermal objectives) require some refocusing when T_{amb} changes. This operation is done manually in the case of portable thermal imagers. The problem is that this manual focusing mechanism cannot be used by the human operator when imager is in the chamber and the operator has no access to the imager. The only solution is to change distance simulated by the collimator to a value that ensures getting a sharp image generated by the tested imager.

It can be estimated that changes of the focus position of IR objectives used by thermal imagers at the typical temperature range from −40 °C to +70 °C are not more than ±0.2% of the objective focal length (typically much less for good athermal objectives). Therefore, a collimator of a variable focus in the range equal to at least ±0.2% of the collimator focal length is needed to compensate variations of the objective focus with variable ambient temperature. Now the conditional requirements (points 7–10) are clarified and a summary for requirements for a dual-chamber system can be presented in a short form in Table 2.

10. Design of a dual-chamber test system

As presented in section 8, the dual-chamber test system is basically a modular system built from three blocks: athermal image projector, translucent imager chamber, and projector chamber. Now, in the next section, design rules of these blocks shall be presented.

10.1. Athermal image projector

A typical image projector used for testing thermal imagers is a system built from four main blocks: collimator, blackbody, rotary wheel, set of targets (Fig. 9). Design of any of these blocks is a technical challenge if the system is to work at extreme temperatures.

The targets are mechanical parts coated with delicate high emissivity coating. This coating can be damaged when subjected to a temperature shock (different thermal expansion of the metal plate and coating) or to ice/water on the surface created when the target plate temperature is below the dew temperature.

Rotary wheels are designed using some control electronics that can be damaged at extreme ambient temperatures. In addition, the performance of lubricants between moving parts can deteriorate significantly at extremely low ambient temperatures.

Blackbodies used in the image projectors can be divided into two groups:

A) blackbodies built in form of two blocks: 1-blackbody head, 2-electronic controller;
B) blackbodies built as one block: integrated head/controller that communicates to PC.

If class A blackbody is to work at temperature chamber, then actually only a blackbody head built using simple electronics (temperature sensor, cable, sometimes A/D converter) is inserted to the chamber. If class B blackbody is to work at temperature chamber, then all sophisticated electronics of such blackbody is subjected to extreme ambient temperatures. Therefore, the design of class B blackbodies is much more difficult than class A blackbodies. However, class B blackbodies offer potentially and significantly much better temperature measurement accuracy and stability when faced with rapid variations of ambient temperature in a temperature chamber. Therefore, it is necessary to design special versions of class B blackbodies with hardened electronics capable to work at extreme temperatures in the chamber.

As shown above, there are technical problems to design well working targets, rotary wheel or blackbody. However, the main challenge is to design the collimator that can fulfil two critical requirements shown in previous section: 1) project images of negligible blurring (collimator resolution over specified level), 2) project images of negligible angular shift (approximately 0.2 mrad).

The deterioration of quality of the projected image by the collimator (image blurring) is caused by four main effects:

Table 2.
Summary of critical requirements for dual-chamber test systems.

Parameter/feature	**Value**
Ability to survive work at ambient temperature from −40 °C to +70 °C	Yes
Ability to display image of targets of regulated shape and size	Yes
Range of regulation of target differential temperature	0 °C to 10 °C
Resolution of regulation of target differential temperature	1 mK
Range of regulation of T_{amb}	−40 °C to +70 °C
Range of regulation of T_{back}	−40 °C to +70 °C
Accuracy of regulation of T_{amb} and T_{back}	+0.1 °C
Optical aperture of the collimator/optical aperture of translucent window	>1.1× aperture of tested imager
Collimator resolution	$\nu_{col} \geq 0.45\ D_{col}$
Flatness of translucent window	Better than P-V 1.6 λ at 630 nm
Angular shift of image projected by the collimator	0.2 mrad
Regulation of position of a focal plane of the collimator	±0.2% collimator focal length

1. defocusing due to thermal expansion of collimator metal case with variable ambient temperature,
2. defocusing due to thermal expansion of collimating mirror along collimator optical axis,
3. deviation of surface of collimating mirror from ideal parabolic shape caused by mirror thermal expansion, mechanical strains caused by mirror thermal non-uniformity, or mechanical strains caused by mirror mounting,
4. image blurring due to deviation of the secondary mirror surface from perfect flat caused by mechanical strains due to mirror thermal non-uniformity, and/or mechanical strain caused by mirror mounting.

Angular shift of the projected image with ambient temperature is caused by two main effects:

1. angular rotation of collimator mirrors (collimating primary mirror and secondary mirror) due to temperature-dependent mechanical strains of mirror mountings.
2. defocusing due to thermal expansion of collimating mirror/collimator case with ambient temperature.

Performance of typical commercially available image projectors for testing thermal imagers significantly deteriorate or even these projectors are damaged when working at extreme ambient temperatures.

It is technically possible to design an image projector that can survive work at extreme temperatures and to significantly reduce dependence of its performance on ambient temperature in the temperature chamber. This aim can be achieved by two main solutions: 1) designing an image projector (collimator, rotary wheel, targets, blackbody) using materials of a very low thermal expansion coefficient: mirrors made from Zerodur glass (or equivalent) and mirror mounts, also collimator case made from Invar alloy or equivalents, 2) using special military class hardened electronics capable of working at extreme temperatures. The first solution has been known and used successfully for decades, especially for space technology [35, 36]. The second solution is commonly used to design electronics for military applications.

The concept of designing athermal image projectors of near perfect thermal stability using materials of very low thermal expansion coefficient has been known for a long time, but it is a challenging task anyway. Both optical and mechanical parts must be manufactured with very high accuracy. What is even more important, all classical mechanical materials like aluminium, steel, plastics should be replaced by materials of very low thermal expansion like Invar alloy. However, there is a commercial problem to use such materials to build athermal image projectors due to high cost of these materials.

It should be noted that the aperture/focal length/mass of collimators used in systems for testing long-range thermal imagers is about 200 mm/ 2000 mm/ 65 kg and that the collimator design is based on the use of large empty cylinders. Cost of the Invar alloy mechanical elements alone needed to build such an image projector can be estimated at over 400000 USD. This price is acceptable for space projects but is too high to build general purpose image projectors used in metrology of thermal imaging.

In such a situation, the author has decided to use potentially cheaper solutions to reduce the potential displacement of optical/mechanical elements of the collimator due to variable ambient temperature:

1. make passive corrections by using materials with ultra-low thermal expansion for critical elements of the collimator,
2. make active correction of both image de-focusing and angular image shift effects.

In detail, passive corrections are in form of:

1. mirrors made from optical material (Zerodur) with a very low thermal expansion – to eliminate deviation from the ideal paraboloid of the collimating mirror,
2. Invar rods connecting the collimating mirror and the flat mirror – to minimize unwanted defocusing,
3. special mounting of the collimating mirror made from Invar alloys – to minimize angular image shift,
4. collimator metal case of increased stiffness – to minimize angular image shift.

Active correction is in form of:

1. special rotary wheel that enables height regulation of targets – to correct defocusing due to the thermal expansion of a collimator metal case/collimator mirror,
2. set of motors at collimator legs that enables angular regulation of the collimator – to correct angular image shift with a variable ambient temperature,
3. internal reference visible camera located inside the collimator – to detect and measure angular image shift.

10.2. Imager chamber

Design of the imager chamber looks much easier than design of the athermal image projector presented in previous section. Basically, it is a small temperature chamber having a translucent window. Therefore, it appears that only a small modification of a typical temperature chamber by making a hole in the chamber wall and inserting an infrared transparent window is needed. This illusion is supported by an apparent market situation.

There are many IR transparent windows optimized to work with thermal imagers offered on the market [37–40]. However, these are low-cost windows of non-specified (practically poor) surface flatness. They are offered to enable a non-contact measurement of temperature of objects located in chambers with limited access. Basically, the thermal imager should see the object through the window and measure temperature of the object of interest. These windows are typically made from CaF_2 crystals or IR transmitting plastics. They are kept thin (below about 3 mm) in order to increase transmission. Such windows expand measurement capabilities of the thermal imagers but are useless to build translucent chambers needed as a block of the dual-chamber test system to be developed.

The flatness of surface of such IR windows is low (worse than 2λ P-V at $\lambda = 630$ nm) due to both low manufacturing accuracy and thinness. Therefore, these windows significantly deteriorate quality of the transmitted image. This deterioration is acceptable for measurement thermal imagers with a typical low resolution but is not acceptable for testing surveillance thermal imagers with much better resolution. In addition, there is a difference in position of the window. For measurement thermal imagers, the window is typically placed at a significant distance from the imager, when for surveillance thermal imagers tested using the transparent chamber method, the window is located at a very short distance from the imager. This difference amplifies influence of the window on quality of the image received by the tested surveillance imager.

Also available on the market are expensive IR transmitting windows with relatively good flatness (flatness at least better than P-V λ/2 at 630 nm), and high transmission in both MWIR-LWIR bands (transmission over about 0.9). They are made from such materials as germanium, zinc selenide, barium fluoride, or gallium arsenide [41–43]. If only MWIR imagers are to be tested, then additional materials can be used such as: silicon, sapphire, calcium fluoride. These professional IR windows are typically offered at sizes up to about 100 mm and at modest flatness of about P-V λ/2 at 630 nm. However, it is possible to order customized windows of a larger diameter (up to about 300 mm) and windows of higher manufacturing accuracy (flatness up to about P-V λ/6 at 630 nm). However, a simple purchase of these near perfect expensive IR windows cannot solve technical obstacles to build a well working translucent temperature chamber.

The temperature chamber window is supposed to work at conditions of a very high thermal gradient. Temperature of one surface of the window can differ from temperature of the other surface by value as high as 60 ºC or more. Such extremely high thermal gradient on a relatively thin mirror generates strong mechanical strains that can distort flatness of the window surface. The result is that even an expensive near perfect single plate window can transmit a perfect image when working at laboratory temperature but will transmit a strongly blurred image when working at extreme conditions (difference between ambient temperatures from both sides is at least 30 ºC).

The analysed situation of a window in temperature chamber resembles the working conditions of IR windows used at aircraft flying at low temperature conditions. Technical problems in designing such windows are not fully solved, too [44].

Finally, the only positive news about the design of the needed translucent chamber is that the requirement for a negligible variation of the image angular shift is easy to fulfil. Variations of ambient temperature can cause some angular variations of the position of the window fixed in the chamber wall. However, if window parallelism is good (below about 30"), then it can be considered that angular variations of the window position cause only totally negligible variations of the angular position of the transmitted image.

In order to eliminate listed earlier defects of the classical single plate translucent windows, the author has proposed a concept of building a new window for a translucent temperature chamber based on three technical ideas:

1. double-plate window instead of typical single-plate window,
2. slanted window instead of typical straight window,
3. optical elements mounted into stress-free optical mount.

The first solution significantly reduces mechanical stress and deformation of windows surfaces due to difference of ambient temperatures at both sides of the window. In the case of classical single-plate windows, the temperature gradient across a thin single plate can be as high as 60 ºC. Even a very small number of *n*-uniformities of the material used to manufacture the window plate will cause mechanical stress on the window and finally degrade its flatness. It should be kept in mind that if the window is to transmit an image without noticeable degradation, then its flatness must be approximately below 315 nm (equivalent to λ/2 P-V at 630 nm).

Double-plate window means that now there are two actual glass plates separated by a thin layer of air like in windows used in buildings. The two glasses have different temperature: one similar to temperature in the chamber, the other similar to temperature in the test room. This significantly lowers temperature gradient for each window in comparison to single glass. Therefore, it can be expected that a double glass window will transmit image without noticeable degradation.

The second solution eliminates the effect that the tested thermal imager can see itself due to reflection from the window glasses surfaces. In detail, this solution eliminates the common situation when a thermal imager can see an image of its cooled IR FPA sensor placed in the centre of FOV.

Mechanical stress can degrade the image similarly to the temperature stress. The third solution eliminates temperature-dependent mechanical stress of the window plates, which eliminates distortion (blurring) of the image transmitted through the window in a similar manner to the first solution.

10.3. Projector chamber

It appears that the projector chamber can easily be purchased on the market. It is basically a large temperature chamber where the image projector can be located. Later only two simple modifications are needed. First, making a hole in one of the walls of the projector chamber. Second, integration of the projector chamber with the smaller imager chamber in such a way that the hole in the wall of the large chamber is adjacent to the translucent window of the imagers chamber. However, a practically simple commercial purchase cannot deliver the projector chamber needed as a part of the dual-chamber test system.

Temperature stability of typical commercially available temperature chambers is too poor to allow the accurate testing of thermal imagers at extreme temperatures, especially to carry out accurate MRTD measurements.

Temperature stability of temperature chambers is defined as short-term variations measured by the temperature sensor inside the chamber after stabilisation [45, 46]. Technical specifications of typical temperature chambers say that temperature stability of such commercial chambers is at the level of ±0.5 °C (option ±0.2 °C) [45, 46]. Therefore, the claim about too poor stability of typical chambers appears as non-logical in a situation when it is known that the performance of thermal imagers only changes in case of significant changes in ambient temperature of more than about 5 °C or even more [30]. However, the claim is true due to the following reasons.

First, typical commercial temperature chambers work in chopped mode (heat/neutral/cool – at least for temperatures below ambient laboratory temperature) to stabilize temperature inside the chamber.

Second, such chambers use a temperature sensor attached to an internal metal case of the chamber. The sensor indicates relatively small temperature fluctuations at the level of ±0.5 °C due to high mass/thermal inertia of the connected metal case but real temperature fluctuations of air inside the chamber can be even ten times higher over this level.

Third, measurement accuracy of MRTD of thermal imagers using image projectors depends on stability of the image projector offset (difference between true radiometric temperature difference and indicated temperature difference). Practical experiments carried out by the author with several commercial chambers have shown that such chambers generate significant cyclic variations of air temperature that leads to relatively fast variations of a radiometric offset of the image projector inside the chamber at the level of 200 mK per minute or more. Variations of offset at this high level lead to very significant errors (over 100%) of the MRTD measurement of thermal imagers. It can be estimated that variations of a radiometric offset of the image projector can be considered as negligible when they are at below 10 mK per minute (about 20 times lower than in typical chamber).

The situation described earlier means that a customized temperature chamber with improved temperature stability is needed. This chamber can be developed by replacing the typical chopped mode of temperature control (three steps of stimulus: heat/neutral/cool) with a control system capable to continuously regulate both heating power and cooling power while keeping strong and near constant air flow needed to achieve good temperature uniformity. Continuous regulation of heat power can be achieved by continuous regulation of voltage applied to the heaters installed in the chamber. Cooling power cannot be regulated by a continuous regulation of voltage applied to cooling compressor because the compression needs near constant power voltage. However, continuous regulation of cooling power of the chamber can be achieved by continuous regulation of the volume of cool air flow mixed with a stronger air flow of neutral temperature.

11. Specifications of dual-chamber test system

The design concept of main blocks of the dual-chamber test system presented in section 10 has been practically implemented. The author has built three main blocks of such a test system (athermal image projector, imager chamber, projector chamber) using the design rules shown in previous section. These design rules can be used to build the blocks optimized for virtually testing all thermal imagers offered on the market. In the present case, a test system coded EXIR3 optimized for testing thermal imagers of aperture up to about 150 mm (great majority of the market) has been developed (Fig. 16).

EXIR-3 allows the simulation of all possible surveillance scenarios met in real applications of thermal imagers. It means that all surveillance scenarios (all combinations of T_{amb} and T_{back}) shown in Table 1 can be simulated.

The EXIR3 test system is built from three blocks: CHI translucent imager chamber, CHP projector chamber, and ADT150 athermal image projector. Technical specifications of these blocks are presented in Tables 3–5.

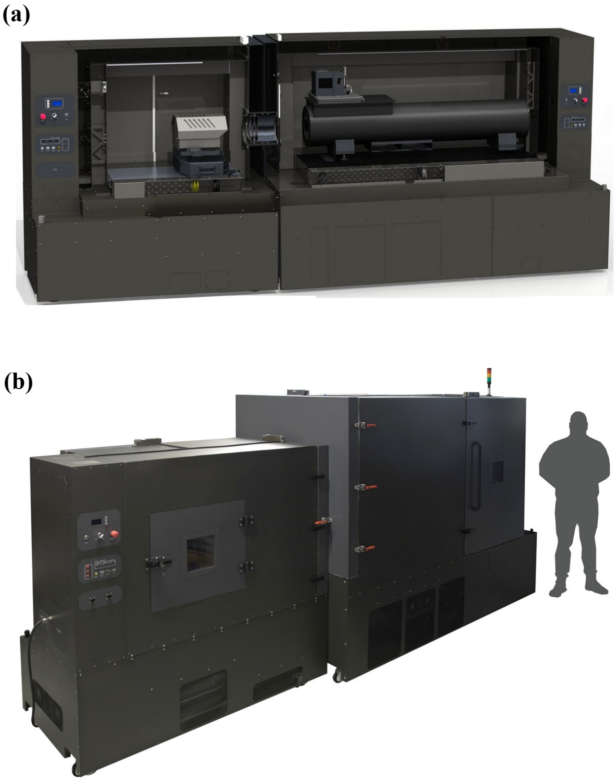

Fig. 16. EXIR3 test system: (a) cross section and (b) photo.

12. Experimental verification

The developed EXIR3 dual-chamber test system is supposed to enable the accurate measurement of the performance parameters of thermal imagers working under a series of working scenarios (different combinations of working conditions: target differential temperature, T_{amb}, T_{back}). However, this hypothesis should be experimentally verified.

There are two main ways to verify performance of EXIR3 test systems.

The first way is to carry out measurements of the main performance parameters (MRTD, MTF, NETD) of several certified thermal imagers and compare the measured results with the results obtained by an accredited laboratory. If the results are similar (preferably near identical), then it means that a given test system works properly. This way is preferable because it could deliver a direct confirmation that the EXIR3 test system works properly. However, this way of experimental verification cannot be practically implemented because there are no certified thermal imagers of known parameters when working at extreme temperatures. In detail, there are accredited laboratories that can measure main parameters of thermal imagers (MRTD, MTF, NETD) and issue proper certificates but only when the tests are done at typical laboratory ambient temperatures [47].

The second way is to prove that two crucial blocks of the EXIR3 test system (the image projector and translucent window) fulfil critical technical requirements presented in section 9:

1. resolution of the image projector fulfils requirements of (2) at any ambient temperature of the collimator in the range from −40 ºC up to about +70 ºC;

Table 3.
Specifications of the ADT150 athermal image projector.

No.	Parameter	Value
1	Aperture	150 mm
2	Focal length	1500 mm
3	Resolution (at any ambient temperature of the working range)	> 140 lp/mrad
4	Angular image displacement (at any ambient temperature of the working range)	< 0.2 mrad
5	FOV	2.3°
6	Differential temperature range of simulated target	from 0 °C to at least 10 °C
7	Resolution of regulation of differential temperature range	0.001 °C
8	Temperature stability	±0.003 °C
9	Control	PC
10	Power voltage	AC 110–230 V
11	Power consumption	< 1 kW
12	Working temperature range	−40 °C to +70 °C
13	Storage temperature range	−5 °C to +40 °C

Table 4.
Specifications of the CHI translucent chamber.

No.	Parameter	Value
1	Internal temperature range	40 °C to +60°C (option up to 90 °C)
2	Window diameter	150 mm
3	Transmission band	at least from 3 µm to 12 µm
4	Max. acceptable dimensions of imager to be tested	1.3 × 0.5 × 0.7 m (length × width× height)
5	Temperature resolution	0.1 °C
6	Temperature stability*	±0.3 °C
7	Temperature uniformity in the chamber	±1 °C
8	Voltage	AC 110–230 V
9	Power consumption	< 1.5 kW
10	Temperature rise speed	1 h (from +20 °C to 60 °C)
11	Temperature down speed	2 h (from +20 °C to −30 °C)
12	Remote control	USB port, communication with PC
13	Working external ambient temperature	5 °C to 35 °C

*temperature sensor attached to a metal cuboid of a mass equal to 0.5 kg that simulates tested imager.

Table 5.
Specifications of the CHP projector chamber.

No.	Parameter	Value
1	Internal temperature range	40 °C to + 70 °C (option up to 90 °C)
2	External dimensions	3.0 × 1.3 × 2.2 m (length × width × height)
3	Max. acceptable dimensions of projector to be inserted	2.0 × 0.9 × 0.8 m (length × width × height)
4	Temperature resolution	0.1 °C
5	Temperature stability*	±0.1 °C/minute; ±0.01 °C/min.
6	Effective radiometric offset of the image projector	< 12 mK/min.
7	Temperature uniformity in the chamber	±1 °C
8	Voltage	AC 110–230 V
9	Power consumption	< 3.5 kW
10	Temperature rise speed	1 h (from +20 °C to 60 °C)
11	Temperature down speed	2 h (from +20 °C to −30 °C)
12	Control type	PC
13	Max. average power consumption of the image projector imager	< 300 W
14	Working external ambient temperature	5 °C to 35 °C

*temperature sensor attached to a rotary wheel used in the reference image projector.

2. deviation of window surfaces from ideal flatness fulfils requirements of (3) at any required temperature difference at both sides of the window (approximately up to 40 ºC).

The task of the ADT150 image projector is to project images in the MWIR-LWIR spectral range. However, the collimator is a reflective optical system that can project images in the visible band, too. Therefore, the author has carried out measurements of resolution of the ADT150 athermal image projector presented in previous section working as a projector of visible images and located in the visible band translucent chamber (Fig. 17). Practically, it means that the following changes have been made in a typical work configuration of EXIR3 systems shown in Fig. 15:

1. IR translucent window of the CHI translucent chamber has been replaced with a window translucent in the visible band,
2. blackbody has been replaced with a visible light source,
3. IR resolution target in form of metal plate sheet with holes has been replaced with a target in form of opaque coating on a translucent glass substrate,
4. thermal imager as an imaging system to record projected image has been replaced with high-resolution VIS camera with a narrow FOV,
5. ambient temperature in the CHI translucent chamber is set to be equal to typical laboratory temperature when temperature in the CHP projector chamber varies in the range from −40 ºC to +70 ºC.

The main advantage of the resolution tests at the visible band is a fact that there are available optical windows for the VIS-NIR band made from materials of near-zero thermal expansion (Zerodur, Astrositall, or equivalents). Therefore, it is possible to build a chamber having a thick optical window characterised by a near-zero mechanical stress. In this way, the translucent window does not degrade the transmitted image at any ambient temperature and the resolution of the collimator can be measured on the basis of the images captured after the window.

As can be seen in Fig. 18, the resolution of the collimator of the ADT150 projector depends on ambient temperature. However, the measured resolution is always higher than the limit according to (2). It means that the collimator influence on quality of the projected image is negligible and acceptable. Additional interesting point is that the best resolution has been obtained not for laboratory temperature of 20 ºC but at higher temperatures of 30–40 ºC. The author cannot be sure about the reasons but suspects that there is some mechanical stress of the mirror at a laboratory temperature of 20 ºC that is reduced at higher temperatures of 30−40 ºC and again increases at even higher temperatures. Situation in case of low temperatures is simpler: resolution decreases with increasing difference from laboratory temperature.

Deviation of surfaces of the translucent window from ideal flatness has been determined using the Fizeau fringes method. In detail, the measurement has been carried out using an optical reference flat in contact with the tested window and being illuminated by a 630 nm laser that produces an image in form of fringes. Deviation from flatness has been calculated on the basis of number of fringes located between the two parallel imaginary lines: one between the ends of any fringe, and the other at the top of that same fringe [48]. The test results show that P-V deviation from ideal flatness of the tested 150 mm diameter window is not higher than 1.25 λ at any temperature difference in the range from 0 ºC to 40 ºC. The tests have been limited to external surface of the first window plane (the surface seen by tested imager). However, it is reasonable to assume that the deviation from the ideal flatness of other surfaces of the tested window is at similar level. It means that the window in the CHI translucent chamber fulfils requirements of (3) at any required temperature difference at both sides of the window and it can be assumed that the window influence on the transmitted image quality is negligible.

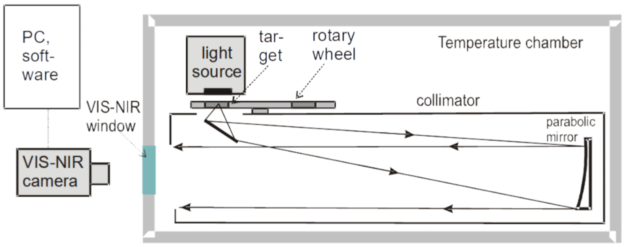

Fig. 17. Concept for measuring the resolution of the collimator of the ADT150 image projector.

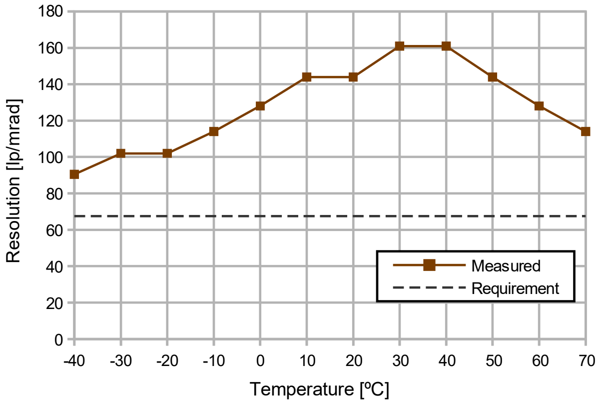

Fig. 18. Resolution of the collimator of the ADT150 image projector at variable ambient temperature [dashed line – lower limit according to (2)].

It should be noted that the test using the optical flat can only be performed when the window plates are uncoated because the coating can be damaged by the optical flat during these contact tests.

To summarise, the obtained test results show that the EXIR3 dual-chamber test system fulfils critical requirements presented in section 9 and should generate accurate thermal imagers tests results at both laboratory and extreme temperatures.

13. Characterisation of thermal imagers at variable working conditions

It is tempting to use MRTD functions measured under a range of different working conditions (at least scenarios in Table 1) to characterise the performance of thermal imagers working under real conditions. However, there are important drawbacks of this solution.

First, MRTD measurements are time-consuming even under typical laboratory conditions. One of the reasons is a significant number of measurement points.

Second, an analysis of the MRTD graphs measured for dozens of working conditions (combinations of T_{amb} and T_{back}) would be difficult and time-consuming.

In such a situation, it has been proposed to characterise thermal imagers to replace a full MRTD function by a set of two parameters that describe extreme limits of this function: imaging resolution and thermal resolution.

Image resolution is a spatial frequency of the smallest resolvable target pattern. Target temperature can be adjusted to the best viewing conditions and is usually high. In the MRTD plot, the image resolution is a vertical asymptote.

Thermal resolution is the minimum temperature difference needed to resolve a large target (low spatial frequency). It marks the beginning of the MRTD curve. The idea of thermal and image resolution is shown in Fig. 19.

Using resolutions instead of the whole MRTD reduces measurement time, as only two measurement points are taken for each tested working conditions. Further on, to make the analysis easier, the measurement results should be normalised to laboratory conditions (Fig. 20).Now, the performance of thermal imagers can be characterised in form of three parameters:

1. classical MRTD measured under laboratory conditions,
2. normalised imaging resolution,
3. normalised thermal resolution.

The set of these three parameters gives all the information needed to analyse the performance of thermal imagers under any work conditions. The measured data should also be easy to analyse.

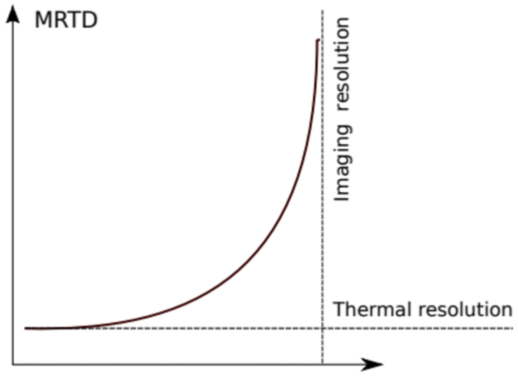

Fig. 19. Concept of determining two limits of the MRTD function

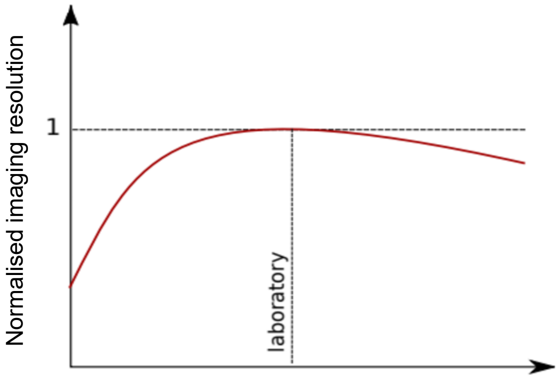

Fig. 20. Concept for normalising the measured resolution.

Similar normalisation concept can be used to normalise measurement results of two other popular parameters: MTF and NETD. They are objective parameters that offer an alternative way to deliver information on imager ability to detect small high-contrast targets or large low-contrast targets. However, the accurate measurement of these parameters of modern thermal imagers is sometimes not possible in case of imagers having an off automatic gain control or/and image processing filters that cannot be fully switched off. Therefore, a classical MRTD can be considered as the safest way for an expanded characterisation of thermal imagers, normalised imaging resolution, and normalised thermal resolution.

14. Preliminary tests of exemplary thermal imagers

The new EXIR3 dual-chamber test system should potentially enable the parameters measurements of thermal imagers at variable T_{amb} and variable T_{back}. In order to preliminary check potential applications of this new test system, the author has carried out tests of a set of seven thermal imagers under simulated variable real working conditions. Two important parameters presented in previous section (imaging resolution and thermal resolution) have been measured.

As stated earlier, the T_{amb} can vary in the range from about −40 ºC up to about +70 ºC. However, this range exceeds the acceptable range of most of thermal imagers offered on the market [49, 50]. Therefore, to limit risk of damage, the imagers have been tested in the reduced ambient temperature range of −30 ºC up to about +50 ºC. The background temperature range has been also reduced to the range from −30 ºC up to +50 ºC in order to reduce the risk of damage to the test system.

Results of these tests shall be briefly discussed. However, manufacturers names and precision data on tested imagers shall not be disclosed due to terms of agreements with suppliers of these imagers that such data shall not be disclosed to third parties. It can be only said that the sample group included both cooled MWIR imagers and non-cooled LWIR imagers. Two of non-cooled imagers failed the tests (electronic problems) and the complete set of measurement results has been obtained only for five thermal imagers.

From the point of view of the measured parameter, the tests can be divided into four groups:

1. measurement of imaging resolution with simulated horizontal configuration (Fig. 21),
2. measurement of thermal resolution with simulated horizontal configuration (Fig. 22),
3. measurement of imaging resolution with simulated slanted up/slanted down configurations (Fig. 23),
4. measurement of thermal resolution with simulated slanted up/slanted down configurations (Fig. 24).

The aim of tests from the first/second groups was to measure imaging/thermal resolution at variable T_{amb}. The results were later normalised to the results obtained at 20 ºC. It should be noted that for these tests, T_{amb} equals T_{back}.

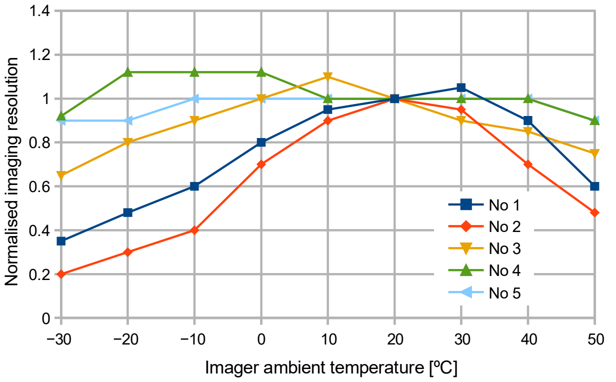

Fig. 21. Normalised imaging resolution *vs.* imager ambient temperature.

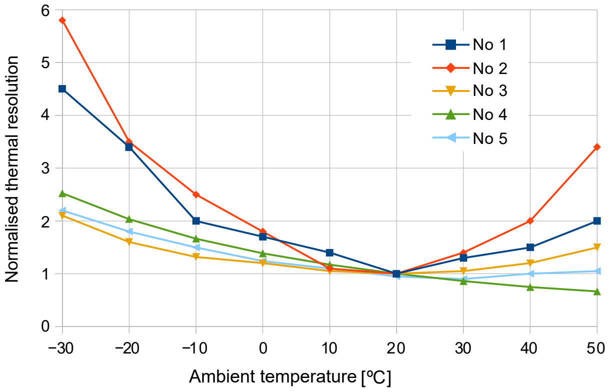

Fig. 22. Normalised thermal resolution *vs.* imager ambient temperature.

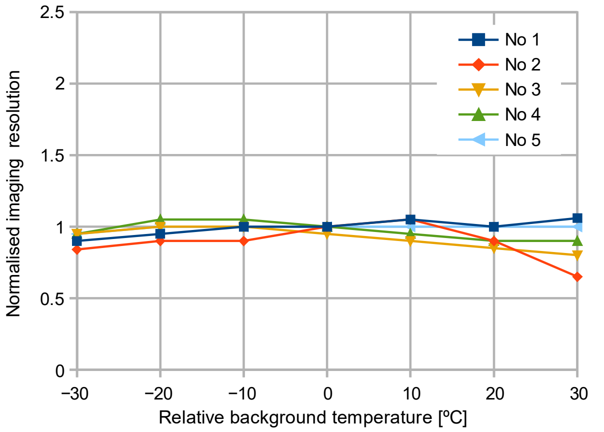

Fig. 23. Normalised imaging resolution *vs.* relative background temperature.

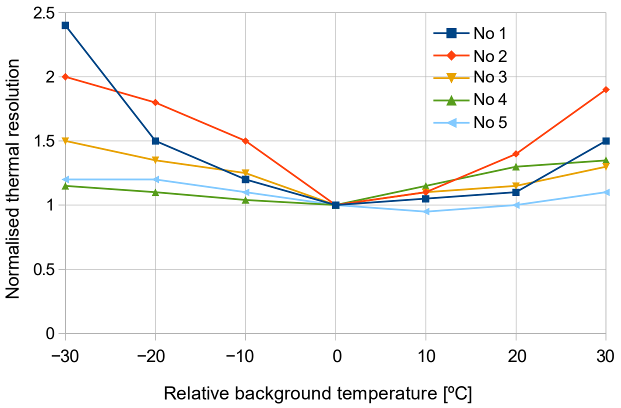

Fig. 24. Normalised thermal resolution *vs.* relative background temperature.

The aim of tests from the third/fourth groups was to measure imaging/thermal resolution at variable background temperature when T_{amb} equals 20 ºC. The results were later normalised to the results obtained when T_{back} equals 20 ºC (relative background temperature equals 0ºC).

When measuring imaging resolution, the aim was to find a target of the highest spatial frequency when bars can still be resolved. In contrast, when measuring thermal resolution, the aim was to find what is the minimal differential temperature of a large four-bar target when bars can still be resolved.

Now, let us discuss the results shown in Figs. 21–24.

The first and most important conclusion is that the performance parameters of thermal imagers offered on the market vary a lot depending on the simulated working conditions. There are imagers that cannot withstand working under extreme conditions (despite catalogue claims) due to reliability problems. Further on, there are imagers that can withstand working under extreme conditions (imagers nos. 1–3) but their performance significantly deteriorates under such conditions (poor imaging resolution and temperature resolution). However, there are also thermal imagers (imagers nos. 4–5) having performance almost non sensitive to work conditions. In detail, there are even thermal imagers (imager no. 4) that offer slightly improved performance at low ambient temperatures compared to laboratory conditions. The test sample was small and it is risky to make such important conclusion but in the author's opinion the conclusion is valid for the market.

The second conclusion is that the performance of thermal imagers is generally more sensitive to T_{amb} than to relative background temperature, especially in case of imaging resolution. This effect is probably related to the fact that the optical performance (blurring effect) of thermal imagers does not depend on background temperature of the target of interest. This relationship is valid only for the performance of thermal camera cores.

The third conclusion is that test data presented in form similar to Figs. 21–24 can be useful for both users and designers of thermal imagers. Such data can give answers to a series of important questions.

Users of thermal imagers:

1. What is a deterioration of the imager performance (range of effective surveillance against target of interest) when the imager works under extreme conditions (extreme T_{amb}, extreme T_{back}) compared to the ranges calculated on the basis of parameters measured under laboratory conditions?
2. Is the imager performance under simulated real working conditions suitable for the planned applications?

Designers of thermal imagers:

1. What is a deterioration of the imager optical performance when the imager works under extreme ambient conditions?

2. Does the image processing algorithm for correcting spatial noise work effectively at any T_{amb}?
3. How big is the apparent increase of temporal noise when looking at targets located at backgrounds of a very low temperature?
4. Are the gain levels of electronic channels set properly? Can the imager deliver sharp images of targets located at backgrounds of a temperature variable in the range of interest or are there cases when the image is saturated?

In case of conclusions for designers, it should be noted that EXIR-3 can be used not only to measure image resolution and thermal resolution, but also directly MTF, NETD, and FPN.

The latter three conclusions show the big potential of the discussed EXIR-3 test station. However, the tests have also shown some limitations of this station.

First, tests of thermal imagers under simulated different working conditions are very time-consuming even if tests are limited only to measure both imaging/thermal resolutions. It can be roughly estimated that at least one hour is needed to measure both resolutions at one ambient temperature (horizontal configuration). That gives about nine hours for limited tests of a single thermal imager to get results like shown in Figs. 21 and 22. The main limiting factor is time needed to change ambient temperature inside both chambers. In detail, it is possible to achieve good speed of regulation of ambient temperature in both chambers, but the main problem is time needed for stabilisation. The reason is that if high accuracy of thermal resolution measurement (low frequency MRTD) is to be achieved, then ambient temperature in the projector chamber must be very stable (rate of change not higher than about 15 mK/min.) Stable ambient temperature in the imager chamber is also needed if stable measurement results are to be obtained.

Second, accurate testing of modern thermal imagers working only in fully/partially automatic mode (no possibility of fully manual mode for image processing/gain/offset settings) is a challenge. The software of these imagers can change the image processing/gain/offset during the measurement process and generate unstable measurement results. The changes can be triggered by the T_{amb} change, reflections in the window, or different shape/size of the projected target. There are cases when accurate testing of such imagers is not possible at all.

15. Conclusions

This paper presents the design, experimental verification, and preliminary applications of a new test system that allows testing thermal imagers under indoor conditions but simulates variable real working conditions. High accuracy of the simulation has been achieved by enabling regulation of two critical parameters that define working conditions of thermal imagers: T_{amb} and T_{back}.

The paper can potentially have a noticeable influence on the future thermal imaging metrology by changing the traditional way of verifying the performance of thermal imagers. Such tests are typically done under laboratory conditions when the test system simulates conditions that differ a lot from real working conditions. The paper has shown that it is technically possible to replace such typical tests with new tests that still can be carried out under indoor conditions (at laboratory), but the new test system can accurately simulate variable real working conditions.

In order to simplify data from tests done at dozens combinations of working conditions (T_{amb} and T_{back}), the paper has proposed to use a set of two parameters: normalised imaging resolution and normalised thermal resolution. These resolutions are normalised against values obtained under typical laboratory conditions and facilitate the analysis of the relationship between imager performance and its working conditions.

The new test systems can potentially also change the situation in writing requirements for thermal imagers in tenders presented worldwide. At present, the tenders typically present technical requirements to be verified under laboratory conditions. This is a typical situation even for a military type of thermal imagers. However, it is probable that in the future most tenders will require measurements of performance parameters under both laboratory and at extreme conditions.

Finally, the test capabilities for the accurate performance characterisation of thermal imagers can speed up the design of the new generation of thermal imagers with improved performance under extreme working conditions.

To summarise, it is clear that the new dual-chamber test system presented in this paper has big potential. However, it should be noted that the tests so far have been limited to a small sample of thermal imagers. The tests have also shown significant limitations of these test systems. Therefore, much more extensive tests and development of detailed test procedures are needed to confirm the potential reported in this paper.

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