Practical approach of thermal lens focus shift with ambient temperature

D. TURCANU[a,*], C. PLESA[a], C. TODIRICA[a], I. NICOLA[a], C. PREDOI[a]
[a]*Military Equipment and Technologies Research Agency, 16 Aeroportului Street, Clinceni, Ilfov, Romania*

The paper presents the work done by the authors in the area of thermal cameras evaluation. Image quality evaluation is an important factor when comparison between specific cameras are to be made. When addressing outdoor thermal cameras, the ambient temperature variation can be a problem for the image quality. The mathematical models were analyzed and many laboratory test were made in order to answer this question: up to what perspective is the focus shift affecting the image quality of a thermal vision system used in normal outdoor climatic conditions?

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1. Introduction

Silicon and germanium are perhaps the two most well-understood semiconductor materials in the context of solid state device technologies and more recently micromachining and nanotechnology. Meanwhile, these two materials are also important in the field of infrared lens design.

In the literature, [1,3-12] there are used several methods to either calculate or measure the refractive index dependency on temperature variations. There are presented in tabulated forms the refractive index values of the most used materials in infrared optics obtained at different temperatures ranging from cryogenic to normal use ones.

Having that in mind, we must admit that something occurs when the temperature varies in a wide field. According to [12], the most significant problem in the infrared is represented by the focus shift with temperature, and the change in refractive index, dn/dt, is tabulated for Germanium.

2. Modelling methods

For a thin lens, the change in focal length with temperature can be expressed as:

$$df = \left[\frac{f}{n-1}\right]\left(\frac{dn}{dt}\right)dt \tag{1}$$

where:

f – focal length;
n – refractive index;
t – temperature.

For a system with a 100mm focal length and a 40oC temperature range, the focal shift is 0.527mm for germanium. This would exceed the Rayleigh limit for acceptable performance of 0.4mm for an F/5 system in the 3 to 5 µm spectral region and of 0.49mm for F/3.5 systems in the 8 to 12 µm region.

Athermalization is the correction of this effect of focus shift with temperature. There are several mechanical and optical methods, active and passive, available to accomplish athermalization. It is possible to solve for achromatism and athermalization at the same time with three infrared materials by solving the following simultaneous equations:

Total power:

$$\sum_{i=1}^{J} k_i = k \tag{2}$$

Achromatism:

$$\sum_{i=1}^{J} \frac{k_i}{V_i} = 0 \tag{3}$$

Athermalization:

$$\left(1+\frac{dl}{dt}\cdot\Delta t\right)\cdot\sum_{i=1}^{J}\left(\frac{dk}{dt}\right)_i + \frac{dl}{dt}\cdot k = 0 \tag{4}$$

where:

k – Boltzmann’s constant, 1.3806x10-23J/K;
V – dispersion;
$\frac{dl}{dt}$ – is the coefficient of expansion of the mounting material;

J – number of lenses.

The above equations can be used to derive an achromatic, athermal hybrid doublet with only two materials if a diffractive surface is considered to be the third material.

Considering the above mentioned aspects, there is a question that should be answered: up to what perspective is the focus shift affecting the image quality of a thermal vision system used in normal outdoor climatic conditions?

The authors propose to answer this question by testing thermal imaging equipment in laboratory conditions in order to easily materialize different ambient temperatures. Several performance parameters are analysed, like focus, NETD (noise equivalent temperature difference) and MTF (modulation transfer function). MTF is the most relevant parameter to be tested when talking about focus shift with temperature. Focus and NETD must be prior evaluated just to have an appropriate image for the MTF test. In the following, the focus and NETD tests are addressed, underlining testing conditions to be considered prior to MTF evaluation.

3. Results and discussions

In the process of testing the performance parameters of thermal imaging equipment, setting an optimal level of focus plays an important role. In the absence of test equipment, the operator adjusts the focus to the clarity of the image seen in the eyepiece or on the thermo-vision equipment screen. In this way, there is a coarse adjustment of target focus but sufficient to operate in real use. When talking about laboratory testing, there are large differences in focus levels following the ESF and LSF curves. Fig. 1 shows two captured images of the same test target at the same temperature difference between the test target and the background but with different levels of focus.

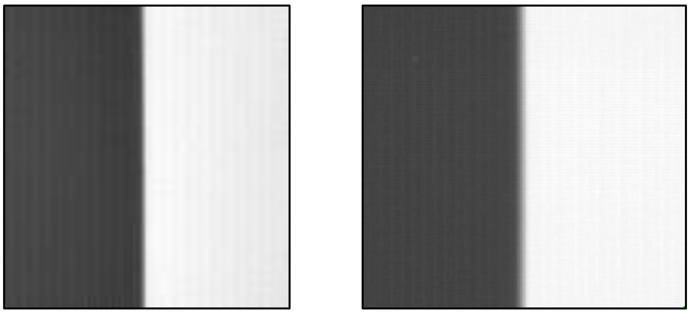


Fig. 1. Different focusing levels

Apparently, following the line of separation between the two signal areas, from the source of radiation and background, no obvious contour differences are observed. Analysing the ESF and LSF graphs, shown in Fig. 2, corresponding to these two image frames, there are clear differences between the two focusing levels.

In the battlefield, this is irrelevant because there are no differences between the images corresponding to these focusing levels. Under laboratory conditions, when it is desired to accurately evaluate the performance parameters of thermal imaging equipment, it is very important to set the correct focus of the equipment, otherwise the measurement results will be negatively affected.

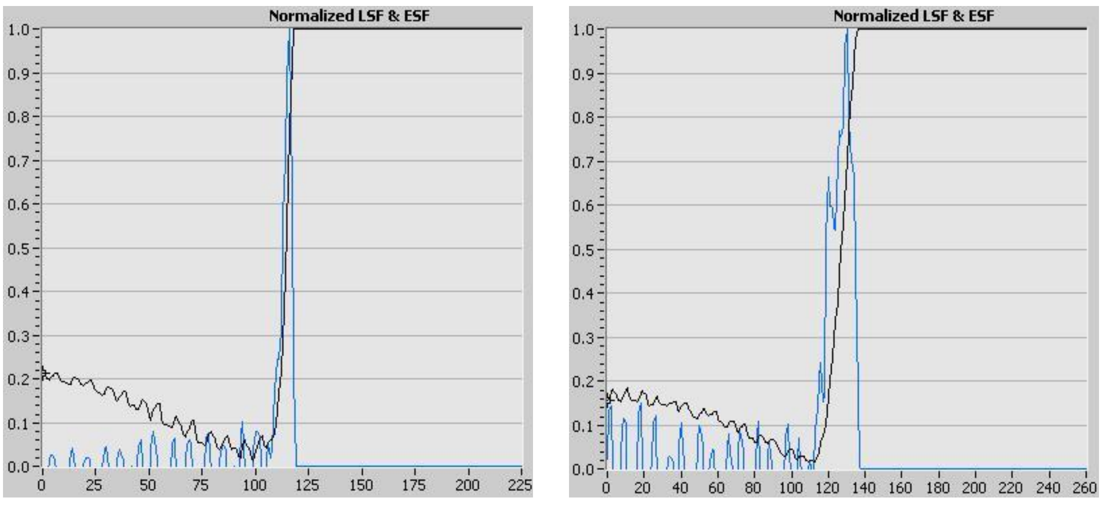


Fig. 2. LSF and ESF charts for the analyzed frames

Focus adjustment must be done in real time to minimize the area below the edge spread function plot (represented by the blue color in Fig. 2).

The uniformity of the image is affected by the focus of the thermal lens.

In general, focusing affects the parameters that depend on ESF and LSF because these lines and contour spreading functions vary with focus. NETD is an intrinsic feature of thermal imaging equipment which, theoretically, should not be influenced by the level of focus adjustment because NETD analyzes two areas of the image that comprise the target signal and the signal from the background, the contour of separation between the two being not subject to analysis. These aspects are also reflected by the results of NETD measurements for the same thermal sensor, the same lens, the same ambient conditions but different levels of focus. NETD charts for the two cases are presented in Figs. 3 and 4.

Fig. 3. NETD chart for good focus

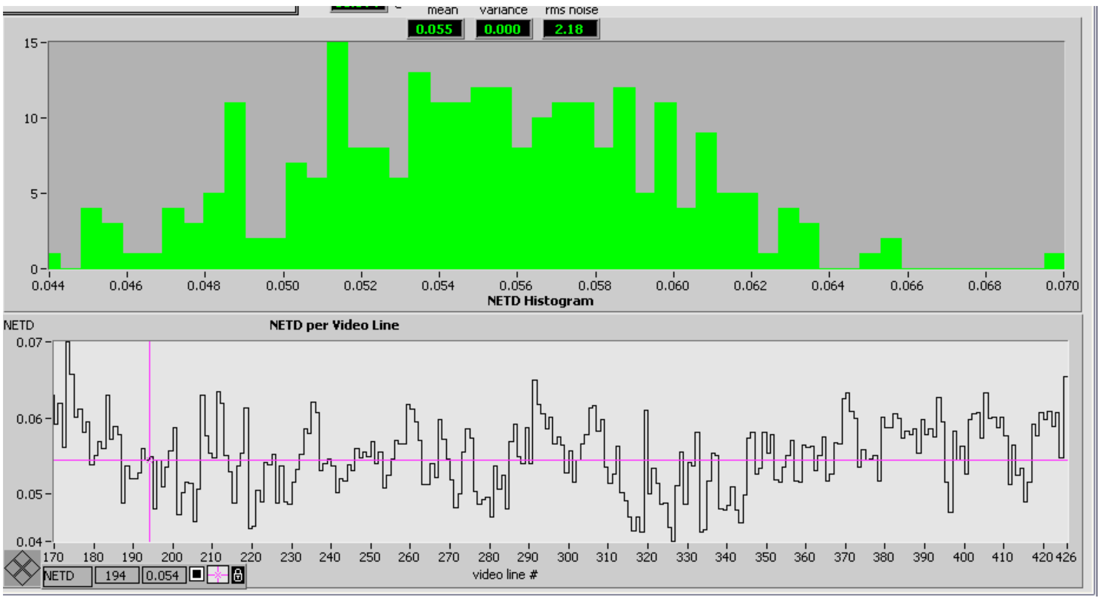


Fig. 4. NETD chart for less good focus

It is noted that the difference between NETD for a good focus, 54mK, and NETD for a less good focus, 55mK, is about 2%, a difference that is covered by the measurement uncertainty of the stand. As expected, the NETD value does not depend on the level of focus adjustment.

Next, some aspects are approached regarding to MTF overall evaluation. Since the form of the image, in a qualitative sense, is closely related to the spatial frequency for which the modulation transfer function is 50%, which allows us to use as the image quality indicator the very value of the spatial frequency for which the MTF takes the value 50 %, images with the same degree of uniformity were evaluated, resulting in a 0.41cy/mrad spatial frequency for bad focusing and 0.46cy/mrad respectively for good focusing. It can be seen that the good focus of the lens allows for a better MTF of 12% than for the less focused focus.

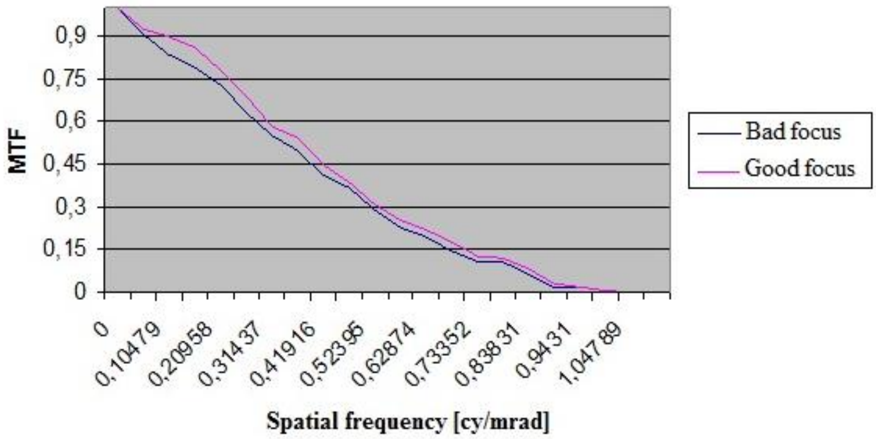
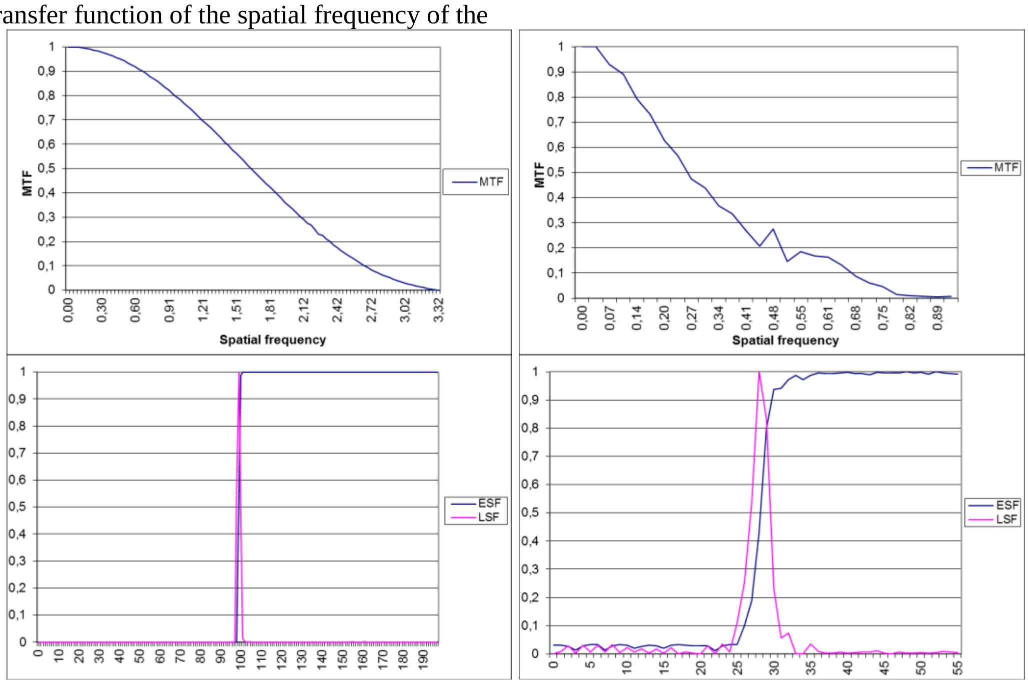


Fig. 5. The MTF chart for the two focusing situations

The modulation transfer function is an important parameter of the thermal imaging equipment considering focus shift effects with temperature. Therefore, the evaluation of this parameter has to be done carefully, especially since the shape of the graph and the values of the results show certain deviations caused by signal fluctuations at the pixel level. Signal values vary over time around the real value, and therefore the shape of the modulation transfer graph does not show the "smoothness" we have learned from visible sensors (see Fig. 6 a and b).

If the modulation transfer evaluation test is repeated, for the same temperature difference between the test target and the infrared source and at approximately the same ambient temperature, it is observed that the plot of the modulation transfer function of the spatial frequency of the test target shows the same shape features; moreover, at certain spatial frequency points, the curve of the function is not a minimum but a maximum value (see Fig. 7 in the circle marked area). These values were obtained for a temperature difference of 5°C between the background and the test target and an ambient temperature of 20 ± 2°C. This variation could be due to ambient temperature variation and the tests showed that for the same ambient temperature value, the shape of the MTF graph is retained (see Fig. 8). These values were obtained from the FLIR SC 4000 thermal imaging camera with a 100mm focal length lens for a temperature difference of 5°C between target and background and ambient temperature Tamb6=18,050°C and Tamb7=18,079°C.



(a) *(b)*

Fig. 6. MTF, LSF, and ESF charts for a) a visible camera and b) a thermal imaging camera

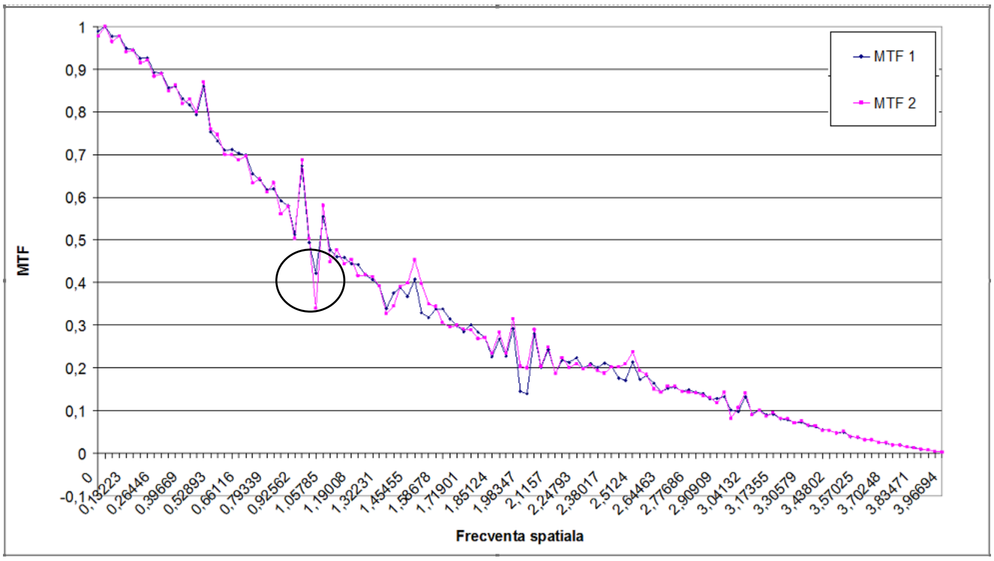


Fig. 7. MTF chart obtained from two tests performed at the same temperature difference, with slightly different ambient temperature

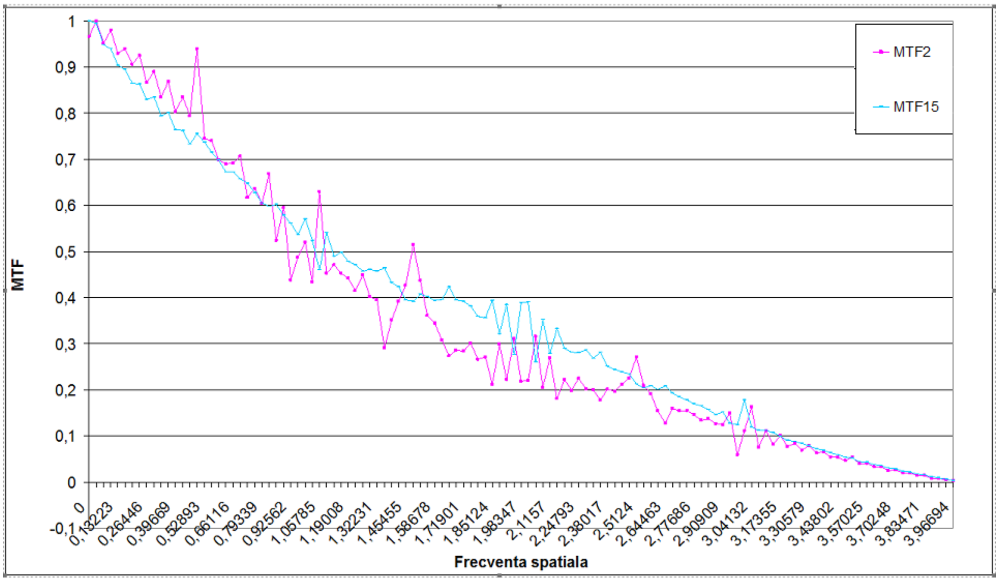


Fig. 8. MTF at the same temperature difference and at the same ambient temperature

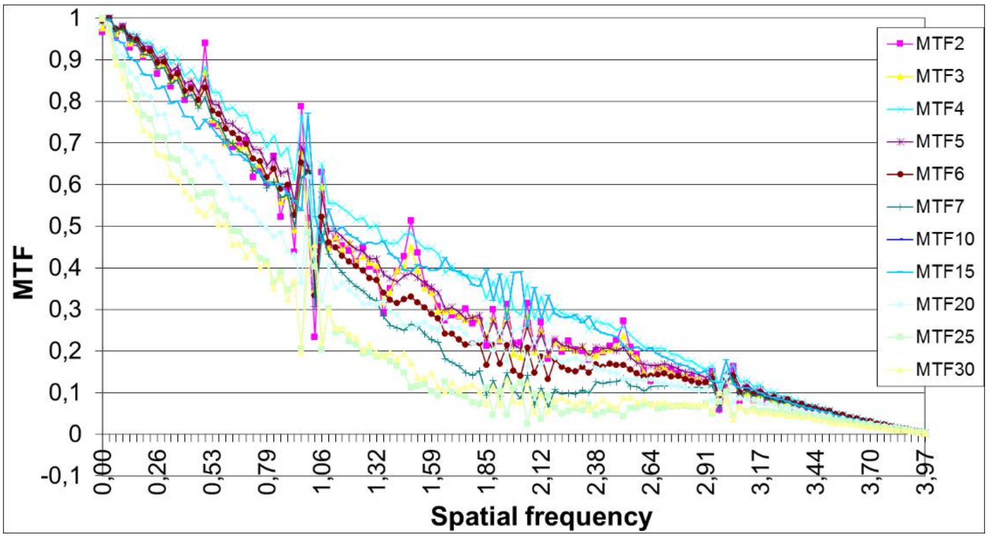


Fig. 9. MTF charts depending on the test target's spatial frequency

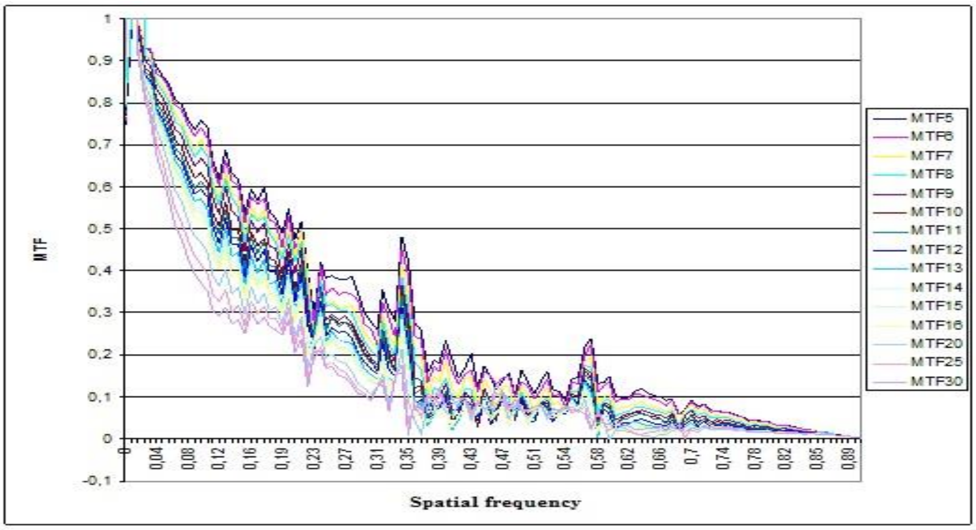


Fig.10. MTF variation for constant Tamb and variable ΔT

So this error of assessment is due to ambient temperature. It is clear that when tests are repeated in a relatively short period of time, special attention will be paid to ambient temperature. Fig. 9 clearly shows the influence of ambient temperature on the test results, ranging from 17,952°C ÷ 21,85°C, as opposed to the results of the tests shown in Fig. 10, when the ambient temperature varied between 16,291°C and 16,36°C during the 15 tests performed.

Analyzing Fig. 10, it is noted that for a temperature difference of more than 20°C the MTF graph no longer has anomalies in the MTF50% area. For temperature differences below 20°C, the MTF curve shows two spatial frequencies for MTF50%. This can mislead the operator, so temperature differences greater than 20°C are preferred. Looking further at the MTF charts, it is noted that the MTF50% value increases with increasing temperature difference. Hence the idea of using large temperature differences, but not saturating the sensor.

4. Conclusions

Analyzing the results obtained during the MTF tests, it is clear that the focus shift caused by the temperature variance affects the image quality of the thermal camera. Running the mathematical calculations numbers are obtained, having no idea how those numbers can be pinned to image quality. The results shown that, when talking about daily outdoor use of thermal cameras, the image quality degradation with the ambient temperature does not affect the purpose of observation and detection of specific objects of interest. This can be done in quite good conditions in an ambient temperature interval from 16°C to 24°C. If radiometric measurements are to be done, the focus shift with temperature plays an important role and cautions must be made in order to obtain concluding results.

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*Corresponding author: turcanued@gmail.com