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Comparison of estimated nominal values of static characteristics based on measurements by different methods

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***Abstract*— One of the quality requirements of thermal imaging devices used in surveillance systems and in forensics refers to the assessment of its capabilities in relation to remote detection, recognition and identification of far-off objects of interest.**

This paper discusses the concept of spatial frequency and compares the estimated values of the nominal static characteristics of the range based on the measurement of the characteristics of a thermal imaging camera according to standard methods (MRTD - Minimum Resolvable Temperature Difference, MDTD - Minimum Detectable Temperature Difference, TOD - Triangle Orientation Discrimination) on an arbitrarily chosen thermal imaging camera.

***Index Terms*— Thermal imaging, spatial frequency, MRTD, MDTD, TOD.**

I. Introduction

Thermal imaging systems are widely used in the field of special purpose devices, because they are based on passive detection. In forensics, these systems are used for the monitoring of objects in motion and for measurements. The assessment of the possibility of remote detection of an object of interest (OI), its orientation, recognition, and identification in space [1,2], is based on the spatial and temperature resolution of thermal imaging systems. Based on the criteria for the visual perception of an OI and the required field of view of the system, the requirement for the instantaneous field of view, i.e. the limiting spatial resolution of the device, is derived. The temperature resolution is considered from the point of view of the sensitivity threshold and the required minimum temperature difference in the OI plane, according to the defined criteria for extracting information from the image and the chosen level of visual perception.

A unique approach to the analysis of spatial resolution was introduced through the concept of spatial frequency for defined periodic spatial distribution of energy (sinusoidal - more suitable for theoretical analysis; or rectangular - more suitable for practical implementation) in object's space. By using a test image with such a periodic structure, it is possible to apply a mathematical model for analyzing the process of image formation, transmission and perception, as well as defining unique criteria for extracting electrical signals in the process of visual information perception. Objective measurement procedures have also been defined for comparing different systems with image formation, based on their ability to distinguish the information contained in the image [1], [2].

Based on the concept of spatial frequency, scene contrast, system resolution, Johnson's criteria for the perception of visual information [1]-[3], mathematical models for characterizing spatial and temperature resolution, measurement procedures were performed to compare the characteristics of different systems, as following:

The MRTD is the lowest value of the equivalent temperature difference between the target and the background that, for a defined spatial frequency, the observer can decompose for an unlimited time of observing the infrared (IR) image [1]-[9].

MDTD is specified for predefined spatial frequencies and is measured using a standard detection test image, where the image dimension is chosen according to the required spatial frequency [1]-[4], [8], [9], [10].

TOD (triangle orientation discrimination) is an alternative method to MRTD that offers a statistically more accurate and less subjective method of characterizing the performance of an electro-optical system for predefined spatial frequencies and is measured using a standard test image for the orientation of equilateral triangles in the plane (four orientations of an equilateral triangle) [11], [12].

This paper presents a comparison of the obtained values of the nominal static characteristics of the range (detection, orientation, recognition, identification) to the OI based on the measured characteristics according to the methods for MRTD, MDTD and TOD in laboratory conditions for an arbitrarily chosen camera and for conditions of attenuation in the atmosphere (atmospheric attenuation coefficients: $\sigma_{good} = 0.2$ [1/km] and $\sigma_{bad} = 1$ [1/km]).

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II. RESOLUTION OF THERMAL IMAGING DEVICES

The repetition frequency of the basic cell in the periodic spatial distribution of radiance is expressed by the number of line pairs per unit length [lp/mm] or per unit angle within the field of view [lp/mrad] or by the number of line pairs per critical image dimension (e.g. lp/(image width)) - which is illustrated in Fig.1.:

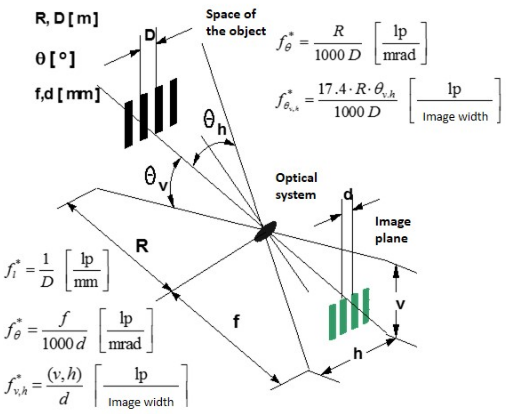

Fig. 1. Geometric relations and definitions of spatial frequency where: R-distance of the object, f-focal length of the lens, D-width of the line pair in the plane of the object, d-width of the line pair in the plane of the image, v,h-dimensions of the image, θv, θh -angular dimensions of the field of view [1]

The transformation of an object into a periodic structure with a known spatial frequency enables the simplification of the content of the visual information on the OI, which is contained within the dimensions of the object, such that the level of visual perception of an object can be related to the critical dimension of the object. Johnson's criteria of visual perception define the critical number of cycles per critical dimension of the object that enables the appropriate level of visual perception depending on the perception conditions. The ***characteristic spatial frequency*** of OI, for a given level of visual perception, expressed by Johnson's criteria, is called such spatial frequency that corresponds to the minimum number of periods per critical dimension of OI, so that:

$$f^*_{vp} = \frac{N_{vp}}{\text{characteristic dimension}}\left[\frac{lp}{unit\ of\ dimension}\right] \quad (1)$$

The ability to separate details in the image is defined by the resolution power, which is expressed by the minimum distance between two distinguishable lines [1], [3].

The results of Johnson's experimental research, which determined the required number of periods (lp) per critical dimension of OI to achieve the appropriate level of perception of visual information, were adopted without significant changes, as a standard for testing devices with image formation, in terms of the quality (level) of visual perception. Table 1 shows the mean values of spatial frequencies for extracting visual information of a given level. The image in the process of transformation retains the same level of perception regardless of the signal/noise ratio, which is high enough, so that the probability of visual perception is equal to unity, that is, the contrast in the basic and transformed image is maintained [1], [3].

Tab. 1.: Critical frequencies for different levels of visual perception

	Number of periods per critical objekts dimension Nvp
Detection	1±0,25
Orientaion	1,4±0,35
Recognition	4±0,8
Identification	6,4±1,5

The temperature resolution of the thermal imaging system is determined, analyzed, checked and considered from two points of view: the sensitivity threshold of the detector (the limit of the detector's ability to extract signals in the presence of noise) and the minimum required temperature differences in the OI plane to enable extracting the information from the thermal image, based on the selected criterion of visual perception. The relationship between the temperature resolution parameters and the construction parameters of thermal imaging devices is shown by the following mathematical-physical models of the characteristics of thermal imaging devices and systems, as follows.

NETD, Noise Equivalent Temperature Difference, is defined as the temperature difference in a standard test image where the signal-to-noise ratio at the output of the video amplifier filter within one video line is equal to 1. It cannot be used as a reliable measure of system quality because it does not include the characteristics of the entire electronics. In practical use, the form of the equation for NETD is most often encountered:

$$NETD\,[K] = \frac{2\sqrt{\pi}\left(\frac{f_o}{D_{tu}}\right)^2 \lambda_p \sqrt{\frac{N_{ps}\cdot F_s\cdot \eta}{n_s\cdot n_p\cdot \rho\cdot p_l}}}{\tau_0\cdot\tau_a\sqrt{A_D}\cdot h\cdot c\cdot D^*_{\lambda_p}\cdot\Phi_o} \quad (2)$$

where: λ_p is the peak sensitivity wavelength of the detector [m], Φ_o is the temperature gradient of the photon flux (limitation by the background photon flux) which at room temperature is approximately $3{,}2\cdot 10^{15}$ [$fotons\ /\ cm^2sK$], τ_0 transmission of optics, τ_a transmission of the atmosphere, A_D area of the detector element [cm^2], D_{tu} diameter of the objective, N_{ps} number of infrared pixels in the image, F_s image repetition frequency, n_p number of parallel detectors, n_s number of serial detectors, ρ scanner efficiency coefficient, η line insertion coefficient and p_l line overlap coefficient [1]-[3], [8], [9].

MRTD is the minimum temperature difference between the "warm" and "cold" fields in the standard test image (3.5 line pairs) for vertical orientation of the test image and is calculated according to the model:

$$MRTD\,(f^*_{px}) = 0{,}744\cdot\left(\frac{S^R}{N}\right)_p\cdot\frac{NETD}{MTF_S\left(f^*_{px}\right)}\cdot \sqrt{\frac{1}{t_e\cdot F_s\cdot\eta}}\cdot f^*_{px}\cdot\frac{\alpha_D}{\sqrt[4]{1+4(f^*_{px})^2\cdot\alpha_D^{\,2}}} \quad (3)$$

where the following new parameters are present: $(S^R/N)_p$ - the signal-to-noise ratio necessary for the required recognition probability p, $\omega = \alpha^H_D\cdot\alpha^V_D$ - the spatial angle that includes the current field of view, the ***MTF$_s$*** - transfer function of the system, t_e - the integration time of the eye (approximately 0.2 seconds) and f_p^* - spatial frequency, which is related to time by the relation: $f[s^{-1}] / f_p^*[lp / mrad] = \upsilon\,[mrad/s]$, where υ is the scanning speed and f is the time frequency [1]-[3], [8], [9].

MDTD is the minimum temperature difference between a square or circular test target and a uniform background, and is calculated according to the model:

$$MDTD\,(f_{px}^*) = 1{,}596\,S' \cdot \frac{NETD}{\overline{I(x,y)}} \cdot$$

$$\cdot\, f_{px}^* \left(\frac{A_{Do}}{\eta F_s t_e} \right)^{1/2} \frac{1}{\sqrt[4]{1 + 4\Delta x^2 f_{px}^{*2}}} \qquad (3)$$

The difficulty of more precisely determining the MDTD arises at the calculating the mean value of the convolution integral for a square target image normalized to the maximum amplitude value [3].

For targets whose area S_T is smaller than the area S of the current field of view at a distance R in the plane of the target, the value $\overline{I(x,y)}$ is reduced to the ratio of the quotient of these areas. In the opposite case, the value $\overline{I(x,y)}$ =1, i.e.:

$$\overline{I(x,y)} = \begin{cases} S_T < S, & S_T / S \\ S_T \geq S, & 1 \end{cases}$$

Applying approximations for small angles, as before, i.e. that $\Delta x \approx \alpha_D^H$, $\Delta y \approx \alpha_D^V$ and $\Delta x \approx \Delta y \approx \alpha_D$, it follows:

$$MDTD(f_{px}^*) = 1{,}596 \cdot \left(\frac{S^D}{N} \right)_p \cdot \frac{NETD}{\overline{I(x,y)}} \cdot$$

$$\cdot \sqrt{\frac{1}{t_e \cdot F_s \cdot \eta}} \cdot f_{px}^* \cdot \frac{\alpha_D}{\sqrt[4]{1 + 4(f_{px}^*)^2 \cdot \alpha^2{}_D}} \qquad (4)$$

where $(S^D/N)_p$ represents the signal to noise ratio for the required detection probability.
That is:

$$MDTD(f^*_{px}) = 2{,}145 \cdot \frac{MTF_S\,(f_{px}^*)}{\overline{I(x,y)}} \cdot MRTD\,(f^*_{px}),$$

where f^*_{px} is the spatial frequency for detection [2], [3], [8], [9].

Mathematical-physical models of the characteristics of thermal imaging devices and systems for $MOTD(f^*_{px})$ (minimum temperature difference for orientation) are derived in a similar way - the minimum temperature difference between 4 triangular test equilateral triangles oriented in all four directions in the image plane; and $MITD(f^*_{px})$ - (minimum temperature difference for identification) - the minimum temperature difference between "warm" and "cold" fields on a standard test image (6,5 line pairs) for its vertical orientation of the test image [9].

III. MEASUREMENT RESULTS

For the thermal imaging camera of a well-known supplier, the following characteristics were measured: minimum temperature differences for detection through tests of a round test target, minimum temperature differences for orientation in space through tests of triangular test targets and minimum temperature differences for recognition through the standard test image of four bars.

The transformation of spatial frequencies into distance was performed using the derived criteria of the number of periods according to the characteristic dimension of OI. Attenuation curves for temperature difference OI (ΔT=2K, 2,3m x 2,3m) and atmospheric attenuation coefficients σ_{good}= 0,2 [1/km] and σ_{bad}= 1 [1/km] [1], [3], [5]-[8], [10] were entered. For the obtained tempera-ture dependences (Figs 2-4):

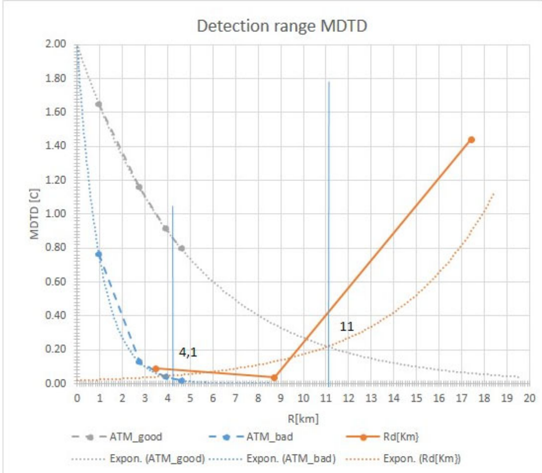

Fig. 2. Detection range - estimated based on measurements

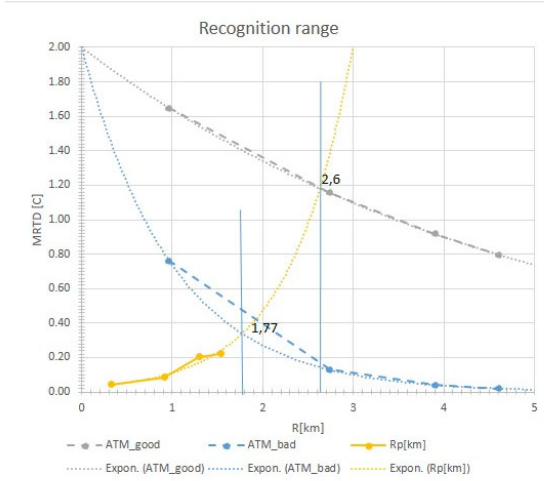

Fig. 3. Recognition range - estimated based on measurements

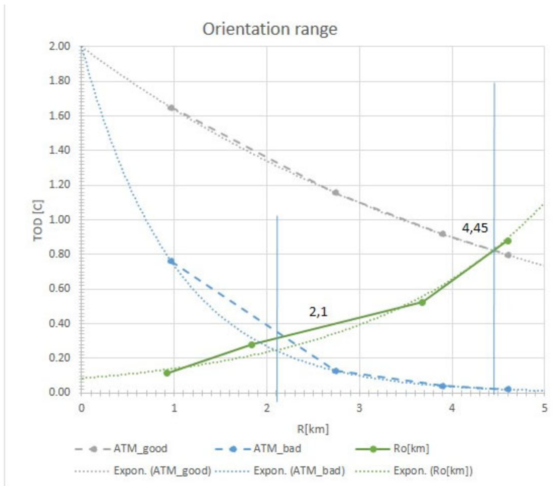

Fig. 4. Orientation range - estimated on the axis of measurement

the parameters were varied in order to compare the obtained range values for the range estimation: detection [D], orientation [O], recognition [R] and identification [I] in the mentioned atmospheric conditions (expressed through attenuation coefficients). The results of varying the parameters when comparing the obtained results are shown in table 2:

Tab. 2.: Comparative results of varied parameters

	σ=0,2[1/km]				σ=1 [1/km]			
	D[km]	O[km]	R[km]	I[km]	D[km]	O[km]	R[km]	I[km]
A	10,3	4,7	**2,6**	1,4	3,6	2,5	**1,77**	1,13
B	**11**	4,85	2,72	1,45	**3,85**	2,7	1,85	1,16
C	10,16	**4,45**	2,9	1,45	2,85	**2,1**	1,55	1,12
The label A refers to the dependences obtained from tests with 4 bars, The label B refers to dependencies obtained through circular tests, The label C refers to dependencies obtained by triangular tests. **Bolded values refer to measurements results**								

Regarding the estimation of the range for the identification of the OI, according to the adopted target and the selected camera, there is a high agreement. In the case of the recognition range, based on the obtained dependencies through triangular tests, for good atmosphere conditions, slightly higher values were obtained compared to the other two applied procedures, while for bad atmosphere conditions, the triangular tests have slightly lower values compared to the other two procedures. When we talk about the ranges for orientation, there is a high agreement of the results where the dependencies with the round and four-bar tests were used, but not with the triangular tests, which for both conditions of attenuation in the atmosphere have slightly lower values. The detection range values are also in agreement. When looking at the estimated range characteristics (DORI) values, the round and four-bar target tests have similar values, while the values obtained with the triangular test target differ slightly.

IV. Conclusion

The presented work showed that the DORI range values of an arbitrary thermal imaging device are comparable through its functions MRTD, MDTD, TOD, and not only through MRTD according to the STANAG 4347 standard [5]. It has been shown that it is necessary to make corrections to the level of visual perception for the application of Johnson's criteria for detraction. When it comes to OI characterized by a small change in temperature difference ($\Delta T=2K$), by the MRTD method, it is 0.4 [lp/critical width of the target-OI], by the MDTD method, it is 2/3 [lp/critical width of the target-OI], and by the TOD procedure, 0.222 [lp/ critical width of the target-OI]. If the temperature differences are an order of magnitude more pronounced and larger ($\Delta T \geq 20K$), by the MDTD method, it is 0.5 [lp/ critical width of the target-OI].

These are not final results. For now, the ways of comparing the methods, as well as the other improvements in the process of measuring different temperature characteristics, shown a high agreement in the obtained results for the DORI ranges of the selected thermal imaging device.

High temperature sensitivity and good spatial resolution make these devices irreplaceable both for continuous monitoring and for monitoring and other measurements in the field of forensic science.

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