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Measurement of basic observation parameters of optoelectronic devices in an accredited laboratory. Measurement methodology, uncertainty analysis

Abstract

The article describes the methodologies for measuring the basic parameters of optoelectronic observation devices in accordance with applicable standards and international procedures. Noise equivalent temperature difference *NETD*, minimum resolvable temperature difference *MRTD*, detection, recognition and identification ranges according to STANAG 4347, angular field of view *FOV* and modulation transfer function *MTF* are described. The description and requirements for laboratory measuring stations are presented. The article contains an analysis of measurement uncertainty of measured quantities in accordance with ISO 17025: 2018 and JCGM 100: 2008 guide based on the TOP 6-3-040 procedure.

Keywords: optoelectronic metrology, measurements of parameters of IR cameras, uncertainty analysis.

1. Introduction

The measurement of optoelectronic parameters of observation devices is aimed at determining their actual performance. The results are helpful in comparing observation systems and choosing the optimal device for a particular applicaton. They are run by producers and independent laboratories. System manufacturers very often give too "optimistic" parameters in the technical specification and do reveal the measurement methodology. Therefore, in many countries there are accredited measurement laboratories enabling the verification of the parameters of observation systems.

Observational optoelectronic systems can be characterized by many parameters. In the Accredited Laboratory of the Institute of Optoelectronics of the Military University of Technology, about twenty parameters of such systems can be measured. For the system user, the most important figures of merit are: the minimum resolvable temperature difference function *MRTD*, detection, recognition and identification ranges, and angular field of view *FOV*. For the system builder the most important is the modulation transfer function *MTF* and noise parameters, in particular noise equivalent temperature difference *NETD*.

2. Measurement methodology

Reliable measurement of optoelectronic device parameters can be performed only under laboratory conditions using specialized equipment and verified measurement methods. The measuring stand consists of: the collimator, the infrared radiation source – blackbody, the radiation source controller, the rotating platform with test patterns, the computer with the measuring cards and specialized software. The properties of the measuring stand itself should have a minimal impact on the measurement result.

Tab. 1. Specifications of SR800R-4D-HE blackbody

Parameter	Value
Aperture	100 mm × 100 mm
Differential temp. range	−30°C ÷100°C
Emissivity	0.98±0.01
Accuracy of temperature	± 0.002°C
Uniformity	±0.01°C

Tab. 2. Specifications of METS S-12 IR collimator

Parameter	Value
Aperture	300 mm
Focal length	1787 mm
Field of view	1.6 °
Transmission	≥0.98 LW ≥0.99 MW
Resolution	Diffraction limitation

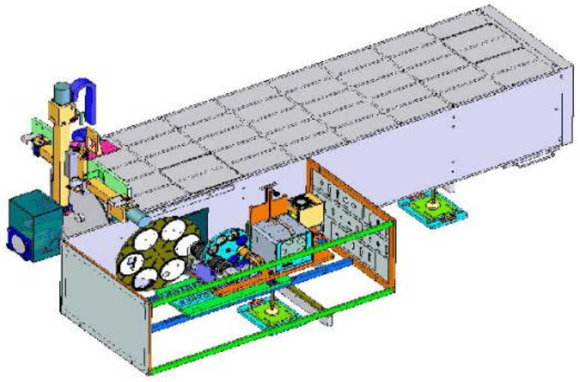

Fig. 1. Test stand for the measurements of parameters of observation optoelectronic devices

The procedures for measuring the basic parameters of optoelectronic devices are well described in the literature [4÷8], and some of them are normalized [1, 2, 9, 10].

The minimum resolvable temperature difference function *MRTD* is defined as the relationship between the minimum temperature difference of the four-bar test and the background temperature, which ensures that all test bars are distinguished by the observer, and the spatial frequency of the test. The procedure for determining the *MRTD* characteristic of thermovision devices is a standardized in NATO STANAG 4349.

In order to determine *MRTD* the minimum temperature difference between the test bars and the background temperature at which the observer is able to distinguish all four test bars is measured. During the measurement process the observer may adjust the values of the electronic track gain, screen brightness, and use other mechanisms of regulation within limits existing in real working conditions, while the observation time is not limited. The tests are carried out first for a positive temperature difference of the test bars with respect to the background temperature and then for a negative difference. The temperature differences at which the observer begins to distinguish all test bars are determined. The final *MRTD* values obtained for a single observer are determined by the formula:

$$MRTD(\gamma) = \frac{\Delta T_{+}(\gamma) - \Delta T_{-}(\gamma)}{2} \quad . \tag{1}$$

where: $\Delta T_{+}(\gamma)$ - *MRTD* values determined for the positive temperature difference between test and background, $\Delta T_{-}(\gamma)$ - *MRTD* values determined for the negative temperature difference between test and background.

It is recommended that measurements should be carried out by three observers without visual impairments [1]. The final measurement results are presented in the form of the average value obtained for all observers participating in the research.

The range parameters (detection, recognition and identification) of observation devices are the most important parameters of observation systems for the user. On the basis of them, one can assess, for example, from what distance it will be possible to recognize a human being in the field of view of the device.

There are several methods for determining the detection, recognition and identification ranges of electro-optical observation devices. The Johnson method is the oldest and most common one [4-8]. This method was accepted by NATO and on its basis STANAG 4347 was developed.

In order to determine the range of detection, recognition and identification it is necessary to:

- measure (or obtain from the technical documentation) the *MRTD* characteristics of the tested device,
- convert the MRTD characteristic to the characteristics of detection, recognition and identification range of the target, taking into account the dimensions of the target:

$$R_D[\mathrm{km}] = D \cdot \vartheta[\mathrm{mrad}^{-1}] \tag{2}$$

$$R_R[\mathrm{km}] = \frac{D}{3} \cdot \vartheta[\mathrm{mrad}^{-1}] \tag{3}$$

$$R_I[\mathrm{km}] = \frac{D}{6} \cdot \vartheta[\mathrm{mrad}^{-1}] \tag{4}$$

where: D – average linear dimension of the target, ν – spatial frequency of MRTD test,

- determine the transmission characteristics of the temperature difference of the target relative to the environment in the atmosphere *ΔT*,
- plot the transmission characteristics *ΔT* of the atmosphere and the characteristics of detection, recognition and identification range of the tested device on one graph,
- on the basis of the graph, determine the detection range as the intersection of the transmission curve *ΔT* in the atmosphere with the device detection curve, the recognition range as the intersection of the transmission curve *ΔT* in the atmosphere with the device recognition curve and the identification range as the intersection of the transmission curve *ΔT* in the atmosphere with the device identification curve, respectively.

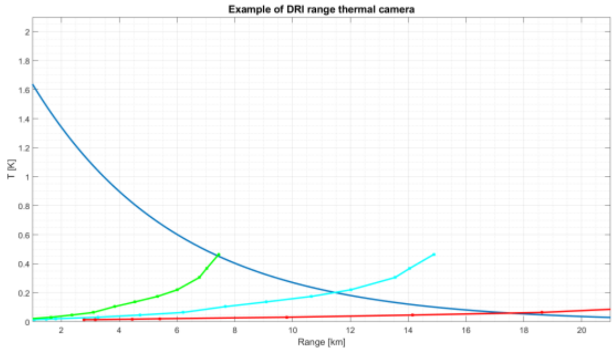

Fig. 2. Example of DRI range

The field of view FOV of a thermal imaging device is a measure of the angle in which a given thermal imaging device carries out image acquisition.

Observation devices may have several values of field of view angles. Measurements should be performed for all available FOV settings. Accurate field-of-view measurements are important because the range of detection, recognition and identification strongly depends on the FOV of the device. Only devices with the same FOV can be compared. The measurements of the angular field of view are usually made using a test with small angular dimensions [11]. Then, the angular positions of the test should be determined in which the test is located at the edges of the field of view of the tested device. Knowing the angular position of the platform with the test positioned at the edges of the field of view, one can determine the FOV of the device using the basic geometric transformations. Test Operations Procedures TOP 6-3-040 allow for performing FOV measurements under field conditions.

Noise equivalent temperature difference *NETD* determines the lowest, theoretically possible to obtain, error of temperature measurement using thermovision devices. It also shows the minimum level of signal reaching the thermal imaging camera coming from the observed target, that the camera is able to detect. *NETD* is defined at the analog video output to the monitor or the digital video output, where the classical external filter is not used (historically, in classical measurement, a simple filter was added with 3-db break frequency equal to the reciprocal of twice the detector dwell time).

In order to determine *NETD* it is necessary to carry out the measurements of the spatial signal noise voltage U_n, the voltage signal value U_2 corresponding to the test temperature T_2, and the voltage value U_1 being the detector's response to the background temperature T_1. Both the test and its background should have a high emissivity coefficient. The difference between background temperature T_1 and test temperature T_2 should not exceed a few degrees. The noise voltage should be measured at the digital output. The device under test should be set to obtain a centrally located test image on its screen. The *NETD* is determined based on the measurement results according to the formula:

$$NETD = \frac{(T_1 - T_2) \cdot U_n}{U_2 - U_1} \tag{2}$$

where: T_1 – background temperature, T_2 - test temperature, U_n – RMS voltage noise, U_1 - RMS background voltage signal, U_2 - RMS target voltage signal.

The test stand in our laboratory provides two method for the measurement of *MTF* characteristics: narrow slit method and edge method. ISO standards recommend slit method [9,10]. However, on the basis of own measurement experience and literature sources it seems that the edge method provides better accuracy and repeatability of *MTF*. There are some variants of this method, but all of them are based on the same principle (Fig. 3). First, the edge spread function (*ESF*) is determined and then the *MFT* is calculated.

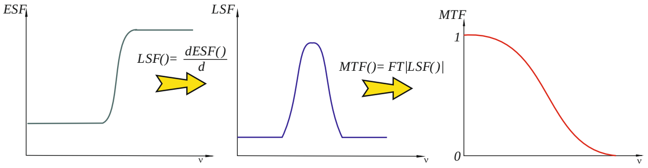

Fig. 3. Determination of MTF function on the basis of measured ESF

ESF function describes the signal distribution in the image of an edge test as a function of position in the detector plane. Edge test should be placed in such a way that its image is parallel to either lines or columns of an array detector.

The procedure of *MTF* calculation on the basis of measured *ESF* function is accomplished in three stages. First the image of an edge test pattern is acquired and an average value of *ESF* function is calculated. Next line spread function *LSF* is determined according to the following relation

$$\boldsymbol{LSF_{ave}(\nu) = \frac{dESF_{ave}(\nu)}{d\nu}} \tag{3}$$

where: $ESF_{ave}(\nu)$ is an average value of an edge spread function, $LSF(\nu)$ is line spread function, ν – spatial frequency.

Because the differentiation increases the amount of noise (so-called virtual noise appears) then prior to this operation the measured ESF function can be substituted by a differentiable mathematical function which provides the required approximation level. Finally, the MFT function is calculated, according to the following equation

$$MTF_{ave}(\nu) = FT|LSF(\nu)| \tag{4}$$

where: $LSF(\nu)$ is line spread function, FT – Fourier transform.

3. Uncertainty analysis

The analysis of measurement uncertainty in the Accredited Laboratory of the Institute of Optoelectronics Military University of Technology is carried out in accordance with the recommendations of the Central Office of Measures [12, 13] taking into account the guidelines of measurement standards and the specifics of measurement methods.

Analyzes of MRTD measurements results are made on the basis of: „Methodology Plan For Resolvable Temperature Difference (*MRTD*) Testing Of Aircraft Installed Sensors” [5]. In order to determine the uncertainty of the measurement result, a mathematical model of the measurement process should be formulated, in which the input quantities should represent all relevant sources of errors. In *MRTD* characterization studies we have the following sources of errors:

- blackbody ΔT source accuracy,
- blackbody temperature drift (stability),
- blackbody uniformity,
- observer standard error of the measurement,
- percent ambient temperature variation,
- percent collimator correction factor.

Blackbody source accuracy ΔT is determined by the specifications of the blackbody and is a measure of the readout accuracy of the blackbody. The uncertainty caused by the inaccuracy of temperature stabilization can be determined from the dependence:

$$u(\Delta T_{BB\_A}) = \frac{2}{3}\tau\Delta t_A \tag{5}$$

where: τ - transmission coefficient of the infrared collimator, Δt_A – error of reading the ΔT of the blackbody.

This blackbody temperature drift is determined by the specifications of the blackbody and is a measure of the readout stability of the blackbody. The uncertainty caused by the temperature drift of the blackbody can be determined from the dependence:

$$u(\Delta T_{BB\_D}) = \frac{2}{3}\tau\Delta t_s \tag{6}$$

where: τ - transmission coefficient of the infrared collimator, Δt_S – the temperature drift of the blackbody.

Blackbody uniformity is determined by the specifications of the blackbody and is a measure of the temperature variability across the surface of the blackbody. The uncertainty caused by the uniformity of the blackbody can be determined from the dependence:

$$u(\Delta T_{BB\_U}) = \frac{2}{3}\tau\Delta t_U \tag{7}$$

where: τ - transmission coefficient of the infrared collimator, Δt_U – the temperature uniformity of the blackbody.

The observer standard error is calculated for each spatial frequency used during the *MRTD* test, such that the variability is frequency dependent. At each spatial frequency, the final averaged *MRTD* and the standard deviation is obtained from the averaged response of each observer. In this way, the final averaged *MRTD* value is evenly weighted for all the observers.

The method of determining the *MRTD* characteristic assumes determining the *MRTD* value as the product of the collimator transmission coefficient and the mean of the sum of the differences between the recorded positive and negative temperature differences ΔT for three observers:

$$MRTD_{obs} = \tau \frac{\left(\frac{\Delta T_+^1 - \Delta T_-^1}{2}\right) + \left(\frac{\Delta T_+^2 - \Delta T_-^2}{2}\right) + \left(\frac{\Delta T_+^3 - \Delta T_-^3}{2}\right)}{3} \tag{8}$$

where: ΔT_+ - positive temperature difference at which the observer begins to distinguish the test bars, ΔT_-- negative temperature difference at which the observer begins to distinguish the test bars.

The above formula can be transformed into the following form:

$$u(MRTD_{obs}) = \frac{\sqrt{\frac{1}{n-1}\sum_{k=1}^{n}((\Delta T_k) - \Delta\bar{T})^2}}{\sqrt{n}} \tag{9}$$

where: n – number of measurements, $\Delta\bar{T}$- the average value of the temperature difference results for which we distinguish the test, (ΔT_k)– the value of the temperature difference results for which an observer distinguishes the test.

Another two sources of errors: change in ambient temperature and collimator transmission factor error are negligible in laboratory measurements and can be omitted.

Summarizing the overall expanded measurement uncertainty of the *MRTD* measurement can be determined from the dependence:

$$U(MRTD) = k \cdot \sqrt{u_{\Delta T_{BB\_A}}^2 + u_{\Delta T_{BB\_D}}^2 + u_{\Delta T_{BB\_U}}^2 + u_{MRTD_{obs}}^2} \tag{10}$$

where: k – coverage factor.

The detection, recognition and identification range is determined on the basis of the measured *MRTD* characteristics. Therefore, the uncertainty in measuring the ranges depends on the uncertainty of *MRTD* characteristics measurement, the number of measuring points and their distribution over the entire measuring range of the *MRTD* characteristic. To determine the uncertainty in the measurement of the range parameters of thermal imaging devices resulting from the uncertainty of determining the *MRTD* characteristics, the uncertainty of measuring the *MRTD* characteristics should be taken into account when determining the intersection points of the atmosphere transmission curve with the detection, recognition and identification curves. The measurement uncertainty determined in this way is about ±5 m.

A much larger uncertainty error in the determination of the range parameters is likely to appear due to limited the number of measuring points. No laboratory has an infinite number of *MRTD* tests. Therefore, based on the literature and manufacturer’s data, it can be stated that the detection, recognition and identification ranges of thermovision devices are not reported with accuracy greater than ±50 m.

According to the *NETD* measurement procedure, the measurement results are several values of noise equivalent temperature difference. Based on the results, one can calculate type A and type B measurement uncertainty. The type A uncertainty is calculated as the standard deviation of the measurement results:

$$u_A(NETD) = \frac{\sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n}(NETD - \overline{NETD})^2}}{\sqrt{n}} \tag{11}$$

where: n – number of measurements, $\overline{NETD}$ - the average value of the *NETD*.

The type B uncertainty is calculated from the dependence:

$$u_B(NETD) = \sqrt{\begin{matrix}\left(\frac{\delta S_{max}}{S_n \cdot \sqrt{3}}\right)^2 + \left(\frac{\delta S_{max}}{S_2 \cdot \sqrt{3}}\right)^2 + \left(\frac{\delta S_{max}}{S_1 \cdot \sqrt{3}}\right)^2 + \\ + \left(\frac{\delta T_2}{T_2 \cdot \sqrt{3}}\right)^2 + \left(\frac{\delta T_1}{T_1 \cdot \sqrt{3}}\right)^2\end{matrix}} \tag{12}$$

where: T_1, T_2, - temperature of the infrared radiation source during the measurement, S_1, S_2 – the average value of the signal voltage for the infrared radiation source temperatures T_1, T_2, respectively, δS_{max} – the maximum measuring error of the data acquisition card specified by the manufacturer.

The total expanded measurement uncertainty is calculated from the dependence:

$$U(NETD) = k \cdot \sqrt{u_A^2(NETD) + u_B^2(NETD)} \tag{13}$$

where: k – coverage factor.

As in the previous method, according to the *Field-of-View* measurement procedure, the measurement results are several values of *FOV*. Based on the results, one can calculate type A and type B measurement uncertainty. The type A uncertainty is calculated as the standard deviation of the measurement results:

$$u_A(FOV) = \frac{\sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n}(FOV_i - \overline{FOV})^2}}{\sqrt{n}} \tag{14}$$

where: n – number of measurements, $\overline{FOV}$- the average value of the *FOV*.

The type B uncertainty is calculated from the dependence:

$$u_B(FOV) = \frac{1}{\sqrt{3}} \cdot \left(\frac{\delta S_{max}}{S_n}\right) \tag{15}$$

where: δS_{max}- the maximum measuring error of the digital protractor specified by the manufacturer, S_n- the value of the *FOV*.

The total expanded measurement uncertainty is calculated from the dependence:

$$U(FOV) = k \cdot \sqrt{u_A^2(FOV) + u_B^2(FOV)} \tag{16}$$

where: k – coverage factor.

The result of measuring the modulation transfer function MTF according to CTE Algorithm Description is the table value and graph. This means that only the type B measurement uncertainty can be determined. Using the mathematical model of the measurement process, the expanded measurement uncertainty can be determined on the basis of:

$$U(MTF) = k \cdot \frac{\delta S_{max}}{S_n \cdot \sqrt{3}} \tag{17}$$

where: k – coverage factor, S_n – the signal value measured on the test surface, δS_{max},– the maximum measuring error of the data acquisition card specified by the manufacturer.

4. Examples of measurement results

In the Accredited Laboratory IOE MUT the most common measurements of thermal imaging cameras are the detection, recognition and identification range. Finally the following data are obtained as measurement results: the table with *MRTD* measurement results, *MRTD* characteristics, *DRI* characteristics of cameras for specific atmosphere and target parameters, table with designated detection, recognition and identification ranges. The table 3 present the results of *MRTD* measurement of a cooled thermal imaging camera with a 3° field of view. With those *MRTD* values, further calculations using NATO target defined by STANAG 4347 and the extinction coefficient of the atmosphere 0.2 km^{-1}, result in the following *DRI* ranges: detection – 11200 m, recognition – 5000 m and identification – 2500 m.

Tab. 3. The results of the *MRTD* characteristic measurement

Spatial frequency lp/mrad	Obs. I K	Obs. II K	Obs. III K	MRTD$_{cor}$(γ) K	U(ΔT_h) K
0.4	0.021	0.021	0.022	0.021	0.007
0.89	0.028	0.025	0.028	0.026	0.007
1.11	0.033	0.033	0.040	0.035	0.007
1.27	0.039	0.038	0.048	0.041	0.008
1.78	0.049	0.047	0.053	0.049	0.008
2.16	0.062	0.063	0.073	0.065	0.009
3.92	0.148	0.148	0.160	0.150	0.010
4.49	0.188	0.175	0.190	0.182	0.012
5.66	0.278	0.265	0.285	0.273	0.013
6.57	0.350	0.330	0.345	0.338	0.020

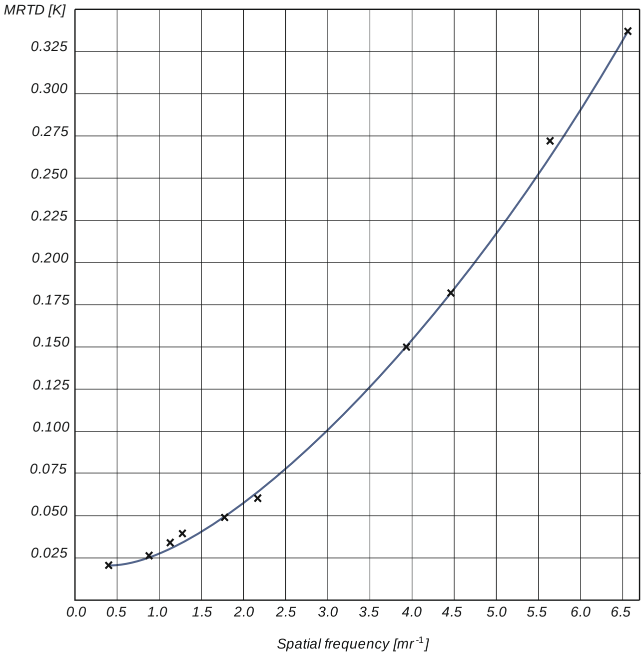

Fig. 4. MRTD characteristic

5. Conclusions

Measurement of optoelectronic devices parameters are described in detail in standards, research procedures and literature. Nevertheless, to perform the measurement well one must have extensive experience and knowledge. Some of the measurements are subjective. However, when comparing the results of the measurement of the same devices made by different laboratories, it can be observed that that the differences in measurement results are not greater than 5%. This is due to the fact that optoelectronic metrology has been reasonably developed for many years along with the development of observation techniques.

6. References

[1] STANAG 4349 "Measurement of the minimum resolvable temperature difference (MRTD) of thermal cameras", (1995).
[2] STANAG 4347 "Definition of nominal static ranger performance for thermal imaging systems", (1995).
[3] PN-EN ISO/IEC 17025:2018-02.
[4] Test Operations Procedures (TOP) 6-3-040 Thermal Imaging Systems, Alabama 2009.

[5] Test Operations Procedures (TOP) 6-3-014 Methodology Plan For resolvable Temperature Difference (MRTD) testing of Aircraft Installed Sensors, Alabama 2011.

[6] North Atlantic Treaty Organization “Experimental Assessment Parameters and Procedures for Characterization of Advanced Thermal Imagers”, (2003).

[7] Gerald C. Holst, Electro-optical image system performance, JCD Publishing Company, 2008.

[8] R.G. Driggers, S.J. Pruchnik, Jr., „Laboratory measurement of sampled infrared imaging system performance”, Optical Engineering 38 (5), 853-861, (1999).

[9] ISO 15529:2010 „Optics and optical instruments: Optical Transfer Function; Principles of measurement of modulation transfer function (MTF) of sampled imaging system”, Edition 3, z dnia 01.08.2010.

[10] ISO 9335:2012 „Optics and optical instruments: Optical Transfer Function; Principles and procedures of measurement”, Edition 2, z dnia 01.10.2012.

[11] CTE Algorithm Description, CI System 2011.

[12] Evaluation of the measurement data – Guide to the expression of Uncertainty of measurement, JCGM 100:2008.

[13] Evaluation of the Uncertainty of measurement in Calibration, EA-4/02 M:2013.

Received: 12.10.2018 *Paper reviewed* *Accepted: 03.12.2018*

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