MODULATION TRANSFER FUNCTION IN THE ANALYSIS OF ELECTRO-OPTICAL SYSTEM PERFORMANCE

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Abstract:

Introduction/purpose: The Modulation Transfer Function (MTF) is a useful tool for an imaging system performance analysis. It is used in Electro-Optical (EO) system design, verification of targeted system parameters, but also in optimization tasks for systems under test. This methodology based on the linear systems theory allows the performance analysis of complicated EO systems to be divided into subsystems. In this paper, the MTF methodology will be presented and explained, followed by the measurements performed in the electro-optical laboratory. The MTF measurements were performed on three types of cameras in different spectral bands, after which the results were compared to the model expectations and theoretical limits for the imaging system. For one of the sensors, the limiting frequency was also measured using the USAF 1951 test target which allowed the comparison between the methods.

NOTE: The previous version of this paper was presented at Sinteza 2019 International Scientific Conference on Information Technology and Data Related Research (Pađen, 2019).

Methods: Laboratory measurements and theoretical mathematical calculations.

Results: Based on the laboratory and theoretical results, the measurement results were further analyzed.

Conclusion: The measurements have proven that the calculated cutoff frequency and the MTF curve represent the limit for the real measured system performance. Therefore, this study has confirmed that the MTF can be convenient for finding system limitations and bottlenecks and for increasing the overall performance of the system.

Key words: MTF-Modulation Transfer Function, USAF 1951 test, electro-optics.

Introduction

Border security in the modern society has become an increasingly important task for countries in order to prevent illegal immigration, smuggling and cross-border criminal, but also to answer to the recent needs for border lockdowns due to the pandemic health crisis (McDaniel et al, 2006), (Dufour, 2013). As borders are vast, usually not easily accessible areas, the task of their protection requires centralized control and integration of various types of sensors such as radars, cameras, motion sensors, and unmanned aerial vehicles. One of the key roles in these systems is the one of Multi-Sensor Imaging Systems (MSIS) which are sets of different sensors covering the visible spectral band (Holst, 2008) - VIS (0.4-0.7 μm), but also the Near Infrared – NIR (0.7-1.1 μm), Shortwave Infrared - SWIR (1.1-2.5 μm), Midwave Infrared – MWIR (2.5-7 μm) and Longwave Infrared - LWIR (7-15 μm) ones. The goal of these systems is to provide all-day, all-weather visibility, which is achieved by integrating high quality detectors working in different spectral bands and powerful lenses, for long range and high resolution systems (Perić et al, 2019). Based on their main role in the system, MSIS can be designed for various tasks such as detection, recognition, and identification of different type of objects (vehicles, trucks, pedestrians, etc.).

This paper will analyze one such multi-sensor imaging system consisting of a visible camera, an SWIR and an MWIR camera with lenses whose specifications will be listed in Chapter 5 of this paper. The performance assessment of this system was done in an electro-optical laboratory by measuring the system Modulation Transfer Function and, for one of the sensors, the resolution using the USAF 1951 resolution test chart.

In Chapter 2, we will describe the basics of the electro-optical (EO) imaging system performance and its main models. Chapter 3 gives an overview of the theory behind the MTF analysis and its contribution in the overall performance analysis of one imaging system, followed by Chapter 4 where the methodology uncertainties and biases are listed.

The laboratory environment, the equipment used for the measurements and the procedures and methods used in this process are described in Chapter 5.

Chapter 6 presents the measurement results for all three sensors and discusses them in relation to the theoretical expectation.

The alternative measurement of system limiting resolution is presented in Chapter 7.

The real-environment outdoor camera performance is presented in Chapter 8 where the system potential to perform detection, recognition and identification of objects is tested on the scene 12 km far from the EO system position.

Finally, the last chapter offers the conclusions on the conducted testing and proposes some possible guidelines for further optimization of electro-optical imaging systems.

Electro-optical imaging system performance

The analysis of the electro-optical imaging system performance is a complex process that must cross-reference the results and information gathered in different environments, as depicted in Figure 1.

Besides the necessity of taking measurements/predictions in various environments, one must take into consideration all the elements of the system, from the scene, to the observer (Holst, 2008).

Figure 2 depicts one such system, and the elemets which are affecting the creation of an image to be presented to the observer.

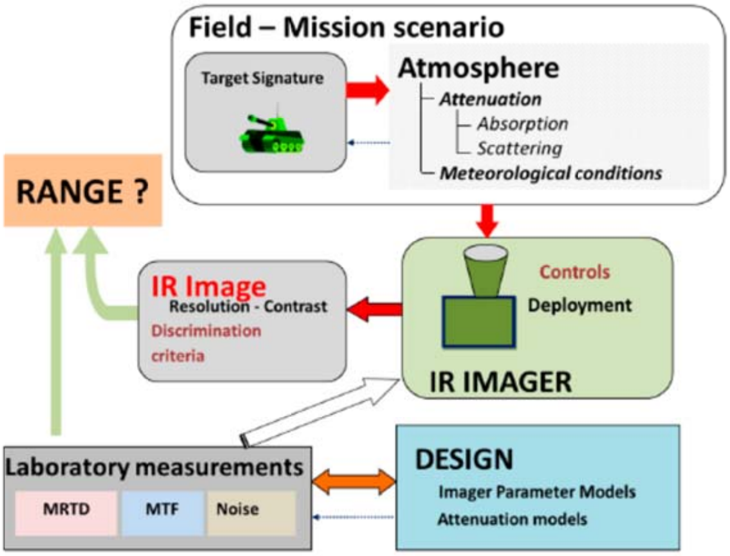

Figure 1 – Relationship between different system predictions and measurements, for an infrared imager (Perić et al, 2019)
Рис. 1 – Отношениемежду различными прогнозами и измерениями системыдля инфракрасной томографии (Perić et al, 2019)
Слика 1 – Однос између различитих предикција и мерења система за инфрацрвену камеру (Perić et al, 2019)

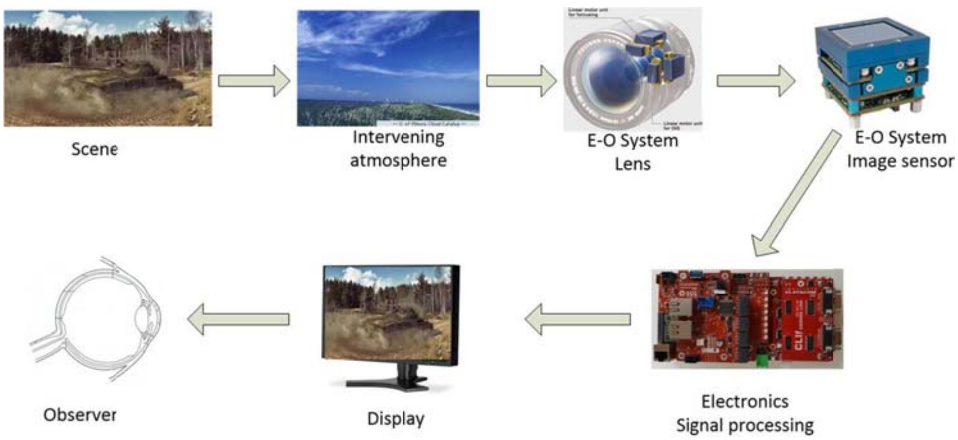

Figure 2 – Electro-optical imaging chain
Рис. 2 – Электрооптическая цепочка изображений
Слика 2 – Електрооптички ланац слике

The major elements that contribute to the resulting image quality are the following (Holst, 2008):

- The scene content - target and background characteristics, clutter, motion
- Intervening atmosphere - rain, haze/fog, transmittance, dust
- Electro-optical system – Lens and Sensor system - Minimum Resolvable Temperature Difference (for infrared systems), Minimum Resolvable Contrast (for visible systems), resolution, sensitivity, noise,
- Electronics – Signal processing
- Display - distance to the observer, luminance, contrast, and finally,
- Observer - his experience, fatigue, training, and workload.

In order to relate these various measurable system design parameters with their operational performance, different models were developed and used. Three levels of models are best answering to these requirements (Shumaker & Wood, 1988), (Fiete, 2010):

- Component/phenomenology models – These models find the MTF of the whole system (MTFSYS) by finding the MTF of individual components, listed in the paragraph above. The MTFSYS is then used as an input parameter for the next-level system modeling;
- System performance models – Built on component models, they describe the total system performance for some controlled tasks;
- Operational models – These models focus only on the overall operational system functionality, where they are used to calculate detection, recognition and identification ranges of the whole system.

The focus of our analysis will be limited to the component model, where the Modulation Transfer Function will be used to describe the signal transfer characteristics of the whole system, and of some of its subsystems.

The MTF methodology and its main characteristics as well as limitations are described in more detail in the following two chapters.

MTF analysis

The MTF analysis is one of the primary parameters used in electro-optical system design, sub-system specification and performance analysis (Holst, 2011).

This methodology carries out the analysis of the total impulse response of the system from the spatial (time) domain to the frequency domain by the means of Fourier analysis. The benefit of this is the replacement of the complex time domain mathematics, involving two-dimensional convolutions, with much simpler multiplications between elements (Boreman, 2001).

The imaging channel response is described by the Optical Transfer Function (OTF), where the Modulation Transfer Function represents the modulus of OTF, i.e. the magnitude response of our optical system to the sinusoidal input signals of various frequencies.

The MTF analysis is applicable only for linear shift invariant (LSI) systems which should modify only amplitude and phase of the target (Holst, 2011). In order to achieve this, four conditions must be met: 1. signal processing is linear; 2. the radiation is incoherent; 3. the image is spatially invariant; and 4. the system mapping is single valued. While these conditions are generally not fulfilled, especially on a microscale, the MTF analysis is a very useful tool in a system performance analysis and comparison and, as such, very much in use in the system design and choice of adequate optical elements (Perić et al, 2018).

The MTF methodology connects two important aspects of the image – its modulation depth (or contrast) and resolution - through the concept of spatial frequency.

The modulation depth is actually a measure of visibility of an image. The finite-size impulse response of the electro-optical system (i.e. not the delta function) decreases the modulation depth of the image, compared to that one of the object (Daniels, 2018).

In image processing applications, a system performance is often described in terms of spatial frequency, defined in the number of *line pairs per mm* (or *cycles per mm*, or cycles per miliradian), where one line pair (or one cycle) represents the closest spacing of black and white bars that can be resolved by the system.

Figure 3 presents the USAF 1951 resolution test chart which is one of the most commonly used targets for evaluating system spatial frequency (United States Department of Defense, 1950). The basis of the chart is a group of three vertical and three horizontal lines organized by groups and elements. A higher group/element number gives a higher number of black and white line-pairs per millimeter, i.e. higher spatial freqency. The chart clearly shows that by increasing spatial frequency (increasing the number of black and white line-pairs per millimeter, noted with a higher group/element number in the figure), it becomes more difficult to distinguish the lines.

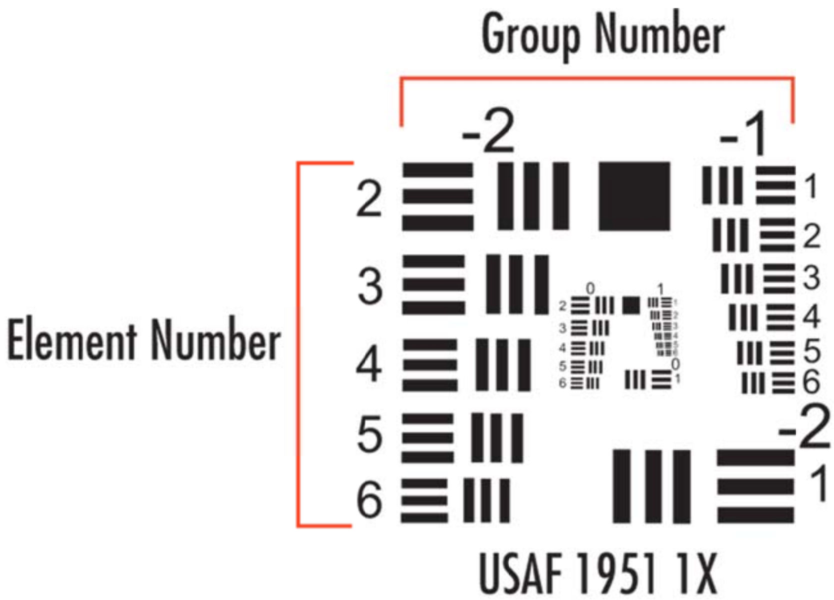

Figure 3 – USAF 1951 resolution test chart, where the group of bars with ahigher group/element number have higher spatial frequencies
Рис. 3 – Тестовая цель ВВС США 1951 года, где группа линий с большим числом групп / элементов имеет более высокую пространственную частоту
Слика 3 – Тестна мета УСАФ 1951, где група линија са већим бројем групе/елемената има већу просторну фреквенцију

The concept of spatial frequency will be additionally explained later in the document, where the system resolution will be evaluated by using the USAF 1951 test chart.

The following figure depicts how the increase of spatial frequency of the object (the upper graph) affects the modulation depth of the image (middle graph), resulting in the degradation of the MTF function (lower graph).

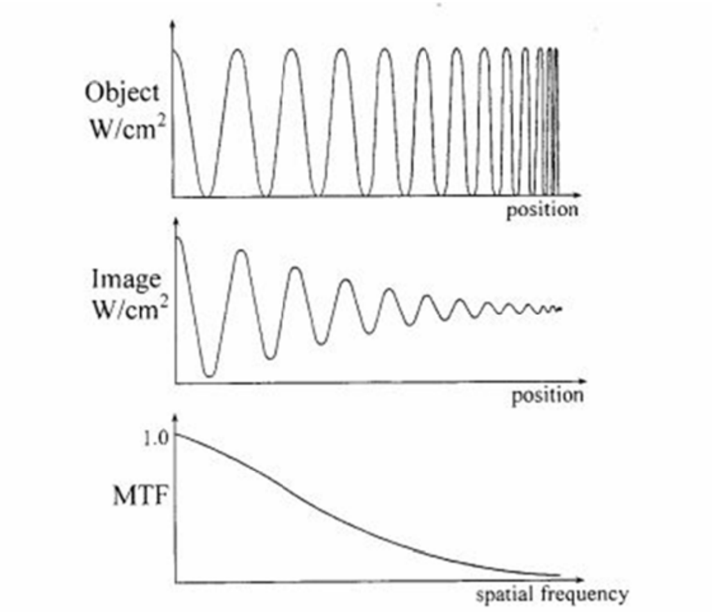

Figure 4 – MTF as a function of spatial frequency (Boreman, 2001)
Рис. 4 – MTF как функция пространственной частоты (Boreman, 2001)
Слика 4 – MTF као функција просторне учестаности (Boreman, 2001)

To summarize, by moving to the spectral domain, instead of convoluting the independent impulse responses of the system components, we will simply multiply their separately calculated MTFs, resulting in the overall system modulation transfer function (MTFSYS). Figure 5 illustrates typical MTF shapes of some of the system components. The x-axis, noted with ξ, represents normalized spatial frequency, i.e. spatial frequency divided with cutoff frequency (detector, or optical cutoff, depending on the type of the system, as explained in Table 1 of this paper).

The MTFs presented in Figure 5 do not conclude the list of the elements affecting the final shape of the MTF system graph, where jitter, defocus and noise also influence the final result. The more components are analysed, the better result (result closer to real measurements) will be achieved. As a rule of thumb, it can be considered that the quality of the optical system is better if the area below the curve is greater. Nonetheless, there is no ultimate way to evaluate which MTF shape is the best (Boreman, 2001), due to non-linearity of the human eye which does the task of reconstruction filtering.

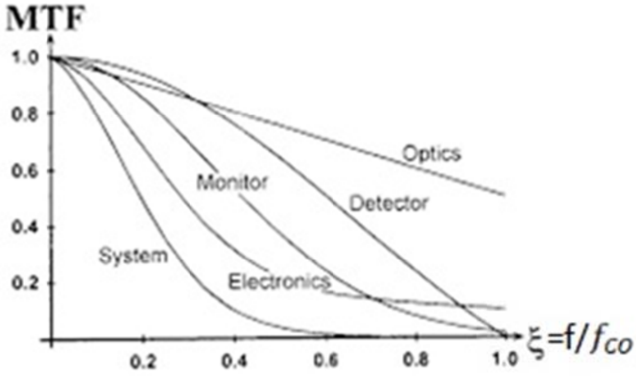

Figure 5 – System MTF as a result of components MTFs, where ξ denotes normalized spatial frequency (Boreman, 2001)
Рис. 5 – Система MTF какрезультат компонентов MTF, где ξ обозначает относительную пространственную частоту (Boreman, 2001)
Слика 5 – Систем MTF као резултат MTF-а појединачних компоненти, где ξ означава релативну просторну учестаност (Boreman, 2001)

The parameter that uniquely defines the shape of the electro-optical system modulation transfer function is given by the expression $F_{\#}\lambda/d$, where $F_{\#}$ is the focal ratio (F-number), λ is the wavelength, and d is the detector size (Holst, 2011).

The following table gives the relation between the value of the expression and its representation in the spatial and frequency domain.

Table 1 – Optics-limited versus detector-limited system performance (Holst, 2011)
Таблица 1 – Оптико-ограниченная эффективность системы по сравнению с детектором (Holst, 2011)
Табела 1 – Поређење система ограничених детектором, односно оптиком (Holst, 2011)

$F_{\#}\lambda/d$	System performance	Spatial domain	Frequency domain
<1	Detector-limited	Airy disc smaller than the detector	Optical cutoff greater that detector cutoff
>1	Optics-limited	Airy disc larger than the detector	Detector cutoff greater than optical cutoff

This ratio also reveals the systems prone to aliasing, boresome artefacts of the signal under-sampling, which occur for the ratios below the value of 2.

While the MTF measurement brings a lot of benefits in system design and analysis, this methodology also has its uncertainties, described in the following chapter.

MTF methodology uncertainties

The MTF laboratory measurement process suffers from various uncertainties or biases, mostly caused by the fact that the methodology requirement for the LSI system is not achieved. This results in differences in measuring which can be categorized into four groups (Haefner, 2018):

- Data corruption,
- Equipment and experimental selection,
- Operator selection, and
- System under test effects.

Data corruption is the reason of the most severe errors in the MTF measurement, which can make the whole process unusable and meaningless. The main reasons of data corruption can be found in:

- Saturation, where multiple input values are mapped to the same output value,
- Quantization, where low signal quantization levels can lead to significant variations in signal output uncertainties, and
- Non-linear response.

Equipment and experimental variations are the reason why the MTF results for the same system, measured in different laboratories, will give different results. These variations are caused by:

- Target angle variations - as the system is not diffraction-limited, the MTF is rotationally dependent

Operator selection, where one needs to select:

- Region of Interest (ROI) - real systems are not spatially invariant, so the choice of ROI will influence MTF measurements,
- Focus adjustment, where results obtained even by highly trained technicians will vary due to selected focuses which will affect measurement results.

System under test effects, such as:

- Non-uniformity, caused by detectors imperfections, poor optics, or fixed patter nnoise, and
- System noise.

While all these challenges in MTF measuring are well documented, with defined best practices how to mitigate these uncertainties, results from the laboratory must be accompanied with the ones from tests performed in real environment, to enhance the evaluation of the system and give clear guidelines for its improvement.

MTF measurement setup

The MTF characteristics measurements were done in an electro-optical laboratory equipped with a collimator station, illustrated in the following Figure:

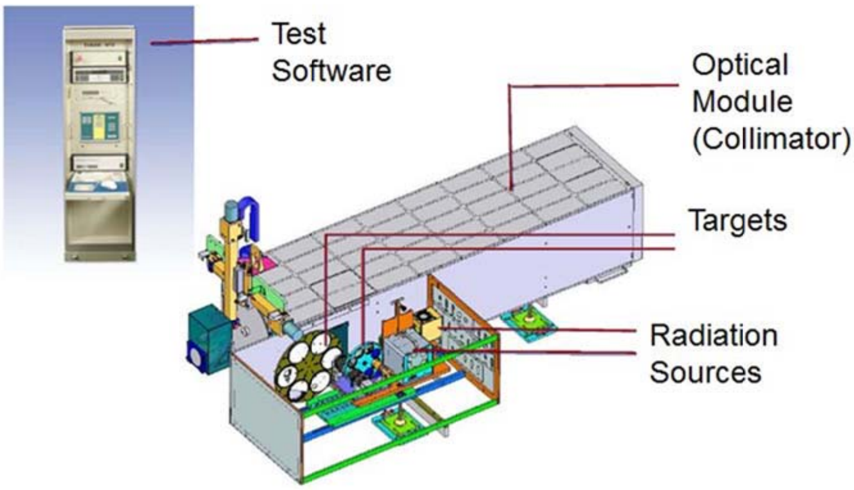

Figure 6 – Electro-optical modular test station (CI Systems, 2012)
Рис. 6 – Электрооптическая модульная испытательная станция (CI Systems, 2012)
Слика 6 – Модуларна електрооптичка тест-станица (CI Systems, 2012)

The test system has the following characteristics (CI Systems, 2012): the collimator's effective focal length (EFL) is 3,025mm (120 inches), with a clear aperture of 355.6mm (14 inch) and a field of view of 1.0º. The radiation source is VIS/SWIR integration sphere with a spectral range of 0.44-2.2 μm, and a blackbody source (absolute temp. range 0°C to 125°C, resolution 0.001°C), which is used for MWIR and LWIR measurements.

The characteristics of the cameras under the test are as follows:

- SWIR – resolution 640 x512 pixels, detector pixel size 15 μm. The lens has a declared waveband of 0.9-1.7 μm, and a

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variable focal length (f_l) of up to 2500mm. The measurements were made on f_l = 2500mm, with $F_{\#}$=16

- Visible camera – resolution 1920x1080 pixels, detector pixel size 5 μm. The lens has a declared waveband of 0.4–0.7 μm, and a variable focal length of up to 2000mm (with extender). The measurements were made on f_l = 2000mm, with $F_{\#}$=16
- MWIR - resolution 640x512 pixels, detector pixel size 15 μm. The lens has a declared waveband of 3–5 μm, an anticipated waveband central wavelength of λ=4 μm, and a variable focal length of up to 825 mm. For the purpose of measurements, we set the focal length to f_l = 784mm, to provide enough room for fine focusing.

There are different methods to determine the system MTF, using the imaging lines, points, or even imagery from a system of well-known MTF values (Schowengerdt et al, 1985).

In this case, the MTF measurements were performed with a step-target, depicted in Figure 7. The MTF measurement procedure with the step target is described in the following lines.

Figure 7 – Step-target, used in the MTF measurement
Рис. 7 – Целевой тест, используемыйпри измерении MTF
Слика 7 – Тест-мета која се користи за мерење МТФ-а

The measurement process begins by selecting and placing the slanted step target with an almost perfect edge in the target wheel, switching on the integration sphere and setting the intensity. The edge spread function (ESF) is the system response to a high contrast edge (Kohm, 2004). Images in a number of consecutive frames are taken, and averaging is done over all recorded frames. The derivative of the ESF produces the line spread function (LSF), which is the system response to a high contrast line. While the target has an almost perfect edge, its image gets distorted as a result of the system imperfection, resulting in the LSF.

From the LSF, by means of Fast Fourier transformation (FFT), the MTF graph is derived, presenting all frequencies up to cut-off frequency.

The above described procedure measured the MTF of the whole system, which was compared with the MTF curves for the detector (determined by the size of the pixel and the focal length of the lens) and the optics system (which is limited by the optical diffraction), calculated from formulas (1) to (5) (Holst, 2008).

The MTF curve for the detector is calculated as the magnitude of the following formula

$$OTF_{detector}(f_x)=\text{sinc}(\pi\alpha_d f_x)=\frac{\sin(\pi\alpha_d f_x)}{\pi\alpha_d f_x}=\frac{\sin\left(\pi\frac{f_x}{f_{DCO}}\right)}{\pi\frac{f_x}{f_{DCO}}}, \quad (1)$$

$$\alpha_d=\frac{1}{f_{DCO}}=\frac{\mathrm{d}}{f_l}=\frac{detector\ pixel\ size}{effective\ focal\ length}, \quad (2)$$

The diffraction (optical) MTF was calculated by the following formula:

$$OTF_{diff}(f_x)=\frac{2}{\pi}\left[cos^{-1}\left(\frac{f_x}{f_{OCO}}\right)-\left(\frac{f_x}{f_{OCO}}\right)\sqrt{1-\left(\frac{f_x}{f_{OCO}}\right)^2}\right], \quad for\ f_x\le f_{OCO}, \quad (3)$$

$$OTF_{diff}=0\ , for\ f_x>f_{OCO}\ , \qquad where \quad (4)$$

$$f_{OCO}=\frac{f_l}{\lambda F_\#}\ and\ F_\#=\frac{f_l}{D}=\frac{1}{2NA} \quad (5)$$

The parameters used in the formulas (and in the tables in the following chapter) are

- λ – central wavelength,
- d – detector pixel size,
- f_l – focal length,
- D – diameter of the lens aperture,
- $F_\#$ – F-number, a function of the focal length and the lens aperture,
- f_{DCO} – detector cutoff frequency,
- f_{OCO} – optical (diffraction) cutoff frequency,
- NA – Numerical aperture, and
- f_N – Nyquist frequency, which is half of detector cutoff frequency, as per the sampling theorem.

Measurement results

The measurement parameters and the calculated cutoff frequencies are summarized in Table 2 for the visible camera, in Table 3 for the short-wave infrared (SWIR) camera, and in Table 4 for the mid-wave infrared (MWIR) camera.

Table 2 – Calculated cutoff frequencies for the visible camera
Таблица 2 – Рассчитанные предельные частоты для камеры видеонаблюдения
Табела 2 – Израчунате граничне фреквенције за видљиву камеру

λ [μm]	Detector size d[μm]	Focal length f_l[mm]	F-number $F_{\#}$	Detector cutoff frequency f_{DCO} [cy/mrad]	Nyquist frequency f_N [cy/mrad]	$F_{\#}$λ/d	Optical cutoff frequency f_{OCO} [cy/mrad]
0.5	5	2000	16	400.00	200.00	1.60	250

Table 3 – Calculated cutoff frequencies for the SWIR camera
Таблица 3 – Рассчитанные предельные частоты для SWIR камеры
Табела 3 – Израчунате граничне фреквенције за SWIR камеру

λ [μm]	Detector size d[μm]	Focal length f_l[mm]	F-number $F_{\#}$	Detector cutoff frequency f_{DCO} [cy/mrad]	Nyquist frequency f_N [cy/mrad]	$F_{\#}$λ/d	Optical cutoff frequency f_{OCO} [cy/mrad]
1.5	15	2500	16	166.67	83.33	1.60	104.1667

Table 4 – Calculated cutoff frequencies for the MWIR camera
Таблица 4 – Рассчитанные предельные частоты для MWIR камеры
Табела 4 – Израчунате граничне фреквенције за MWIR камеру

λ [μm]	Detector size d[μm]	Focal length f_l[mm]	F-number $F_{\#}$	Detector cutoff frequency f_{DCO} [cy/mrad]	Nyquist frequency f_N [cy/mrad]	$F_{\#}$λ/d	Optical cutoff frequency f_{OCO} [cy/mrad]
4	15	784	4	52.27	26.13	1.07	49

These values were then used to calculate and plot the graphs for the MTF of the detector, the MTF of the diffraction, and the resulted MTF of the system (MTF product) using formulas (1-5), given in the previous chapter. The graph X-axes are all plot up to the Nyquist frequency (which is one half of the sampling frequency), as that is the highest frequency which can be faithfully reconstructed, as per the sampling theorem (Holst, 2008).

Figure 8 presents the graphs of the calculated MTFs and the measured MTF for the visible camera with the extender (f_l =2000mm).

Figure 9 gives the graphs of the calculated MTFs and the measured MTF for the SWIR camera with a focal length of 2500mm.

Finally, Figure 10 shows the MTF calculations and measurements for the MWIR camera with a zoom lens with the maximum focal length of 825mm, which was set on 784mm for these measurements.

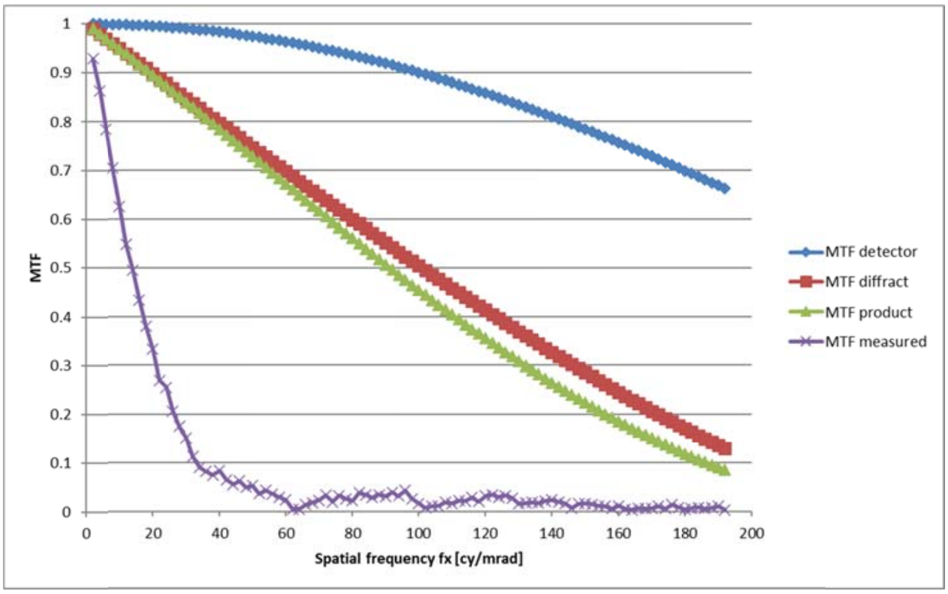

Figure 8 – MTF for the visible camera, f_l=2000mm
Рис. 8 – MTF для камеры видеонаблюдения, f_l =2000mm
Слика 8 – MTF за видљиву камеру, f_l =2000 mm

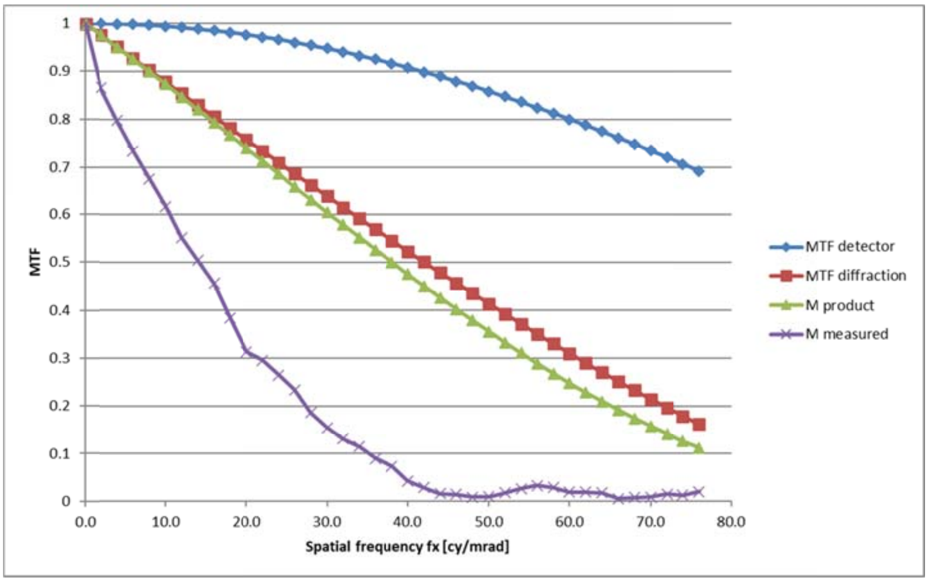

Figure 9 – MTF for the SWIRcamera, f_l =2500mm
Рис. 9 – MTF для SWIR камеры, f_l =2500mm
Слика 9 – MTF за SWIR камеру, f_l =2500 mm

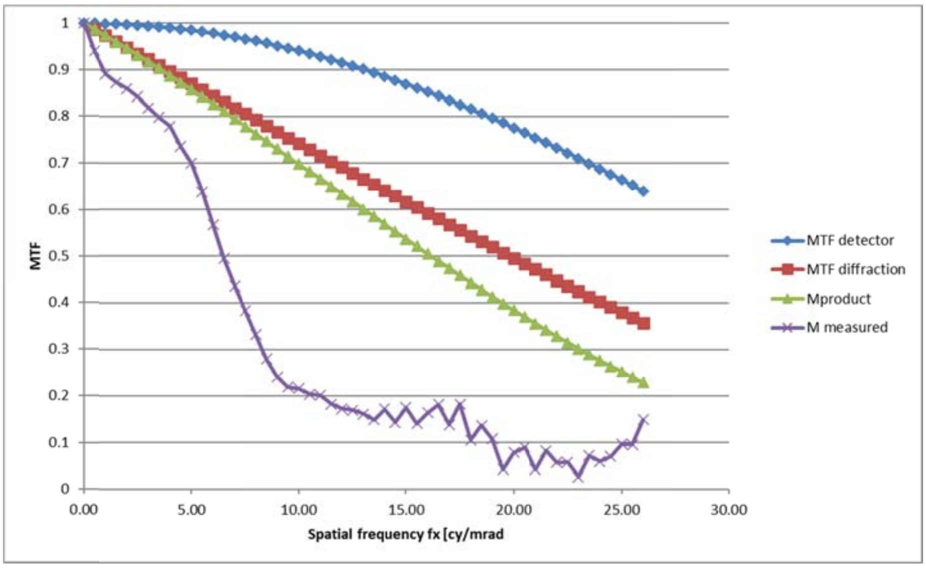

Figure 10 – MTF for the MWIR camera, f_l =784mm
Рис. 10 – MTF для MWIR камеры, f_l =784mm
Слика 10 – MTF за MWIR камеру, f_l =784 mm

A. Visible camera, with the extender (f_l =2000mm)

By analyzing Figure 8, we can conclude that the measured result (the MTF measured curve) has lower cutoff frequency than the one expected by the theory (the MTF product curve). The deviation of the measured MTF from the theoretical one, reflected in the steeper decline of the MTF curve, can be explained by the effect of the elements which were not measured in this case, such as focus, electronics for video processing, display, etc. We can also conclude that the limiting factor in this case is the diffraction of the lens system (f_{OCO}), as the MTF diffract graph is below the MTF detector. While the calculated diffraction of the lens system is at 250 cy/mrad, we can see that the measured MTF is falling below 0.2 already for the spatial frequencies at a one tenth of the optical cutoff. This can be explained by using the optical extender (to achieve the targeted focal length) which has also introduced the deviations caused by the aberrations (imperfection) of the optical extender elements.

B. SWIR camera, a focal length of 2500mm

This measurement, performed by the short-wave infrared camera with a narrow field of view (NFOV), reveals that again we are dealing with an optics-limited system, which is obvious from the graph (where the MTF diffraction is lower than the MTFdetector line), from the values of $f_{DCO}$and f_{OCO}, but also from the value of $F_{\#}\lambda/d$ expression, as per the limits defined in Table 1 of this paper. The MTF measured curve is also below the MTF product one but, compared to the visible camera in the scenario A, the measured curve is less steep. In this scenario, the measured MTF drops below 20% approximately at a value of 26 cy/mrad, which is around 25% of the optical cutoff. Based on this, it is safe to conclude that the SWIR lens has better optical characteristics than the one used with the visible camera. Having this in mind, we expect better identification in SWIR images which will be tested with images taken from a real scenario.

C. MWIR camera, a focal length of 784mm

Unlike the first two scenarios where the system was clearly residing in the diffraction (optics) limited part, here the cutoff frequencies (detector, and optical) are much closer, resulting in closer MTF detector and MTF diffraction graphs, compared to the first two scenarios. What is also readable from the graph is that the measured MTF is above 10% for most of the values up to the Nyquist limit, which is a general indication of a well-designed system and better image quality (Boreman, 2001) (although the system performance can be really evaluated only through the prism of frequency specific range of interest). What also must be commented is the measured results for the frequencies above 22-23 cy/mrad, reflected in the incline of the graph-line. As this have no explanation in physics of the system, this behavior can be explained by system non-linearity, signal processing, measurement setup, and other aspects which are described in Chapter 4 of this paper and have the effect on the MTF measurements.

Other methods for measuring EO system resolution

The MTF analysis and measurements, presented in the previous chapters, offers a lot of information to the viewer, by describing the system behavior on the whole spectrum of frequencies, up to the limiting, cutoff frequency. There are other methods to measure optical resolution: the United States Air-Force (USAF) 1951 resolution test chart, being one of the most popular ones, is given in Figure 11 of this document.

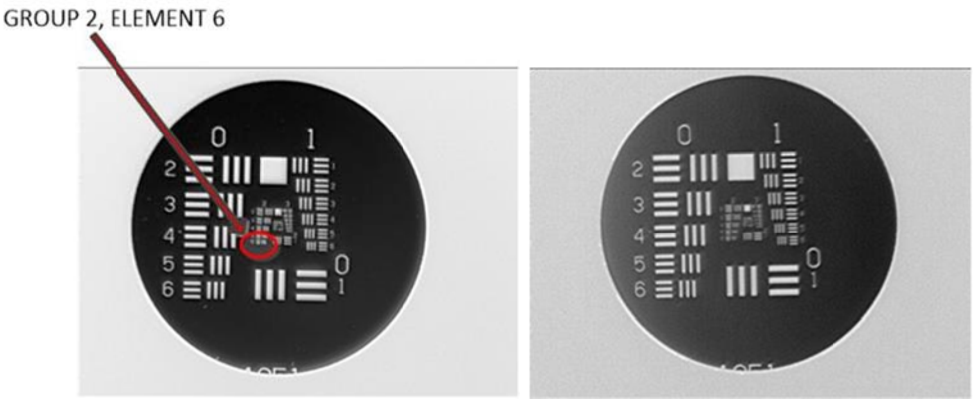

Figure 11 – USAF resolution target, imaged with the MWIR camera described in Chapter 6. The left image was taken with a good focus, the right one with a bad focus.
Рис. 11 – Цель разрешения ВВС США, полученная с помощью камеры MWIR, описанной в главе VI. Левое изображение было получено прихорошей фокусировке, правое приплохой фокусировке.
Слика 11 – USAF-ова резолуциона мета снимљена MWIR камером описаном у поглављу VI. Слика лево снимљена је са добрим фокусом, а слика десно са лошим фокусом.

This target consists of a group of elements, each element consisting of three vertical and three horizontal bars of precise width. The observer task is to visually identify which group of bars can still be distinct without blurring into one another. By identifying the number of that last resolvable element, which is in our case group 2, element 6, the resolution limit can be calculated from the formulas:

$$Resolution\left(\frac{lp}{mm}\right) = 2^{Group+\frac{element-1}{6}} = 2^{2\frac{5}{6}} = 7.13\,\frac{lp}{mm} \qquad (6)$$

$$Resolution\left(\frac{cy}{mrad}\right) = Collimator\ EFL\ [mm] * 10^{-3} * Resolution\left(\frac{lp}{mm}\right) = 21.56\ \frac{cy}{mrad} \qquad (7)$$

where the Collimator Effective Focal Length (EFL) is 3,025mm, as previously mentioned.

Having in mind that the human visual system can work with contrast which is above 5% (although this cannot be taken as a hard fact, as it depends on the human visual system properties), by analyzing again Figure 10, we can see that the value of the MTF is falling to 5% somewhere around the spatial frequency of 20 cy/mrad, which is similar to the limiting resolution found with the USAF 1951 test target (formula 7).

The USAF target, as shown, is an effective method to quickly estimate the system resolution, but it suffers from some challenges. The most important one is in the fact that the process heavily depends on the observer (and his decision on what target is resolvable), but also on some other things, such as the image focus, which can seriously affect the measurement, as shown in Figure 11.

While the MWIR system and the focal length forming the target image were the same for both images, the focus of the object (target) for the right image was not done properly. As a result, the limiting resolution derived from this image is lower than previously estimated. While the matter of the focus is also affecting the MTF calculations (Holst, 2008), (Haefner, 2018), in this case of the USAF1951 test target, it will give a completely wrong picture of the system capability.

Real scenario images

In order to illustrate the image performance of the multi-sensor imaging system (MSIS) in a real scenario, the system tested in the laboratory (a Visible and an SWIR camera, without an MWIR sensor) was installed outdoors and set to monitor the scene approximately 12 kilometers apart from the MSIS position.

Figure 12 – Visible camera image
Рис. 12 – Изображение с камеры видеонаблюдения
Слика 12 – Слика снимљена видљивом камером

Figure 13 – SWIR camera image
Рис. 13 – Изображение с SWIR камеры
Слика 13 – Слика снимљена SWIR камером

What is clearly distinguishable in the pictures are vehicles, buses, pedestrians and the general background characteristics (buildings, trees, etc.). Since this type of system is generally designed to perform detection, recognition and identification of objects, it is safe to say that the system is performing well for the purpose it was built for. Comparing the images in VIS and SWIR, we can conclude that the SWIR image is richer in detail, which is expectable regarding the comments stated earlier in the paper. During the tests, we also noticed remarkable advantage of the SWIR image in the presence of fog.

Conclusions

The theoretical analysis and laboratory measurements of electro-optical system performance have demonstrated that the MTF can be an effective analytical tool.

Theoretical calculations have shown that the increase of the focal length results in the increase of the F-number ($F_{\#}$), and for that reason the diffraction of the lens system becomes the dominant limitation factor compared to the detector limitation. In that way, we have identified the maximal frequency for our system.

The MTF measurements in the electro-optical laboratory have given some valuable information. Besides a visual confirmation on the system limiting elements (where the lower diffraction lines prove they limit the system, and not the detector), the comparison of the curves for VIS, SWIR and MWIR cameras has shown that the SWIR and MWIR lenses have supreme optical characteristics compared to those of the VIS camera. In addition, the visualization of the results in the form of graphs has clearly shown the areas where the system non-linearity and various forms of data corruption caused the graph to behave unexpectedly.

The resolution measurement using the USAF target has presented the alternative ways to analyze the system performance, although less accurate compared to the MTF measurement methodology.

With the real scenario images, we have confirmed the expectation from the laboratory measurements that the SWIR camera gives a better (richer in detail) image compared to the Visible camera. This was especially obvious for the tests conducted in the degraded environmental conditions (fog).

Taking into account the considerable distance, it can also be concluded that the whole EO system performs well, for the purpose it was built for (detection, recognition and identification of objects). This leads to a general guideline in the design and optimization of EO systems – the key of success is to fully understand the system requirements and the use-cases (Hobbs, 2000), since no system can be designed to provide perfect resolution, contrast, brightness and color fidelity, for any object distance, in all possible environmental conditions. Therefore, the best systems are the ones designed for the exact purpose. Then, through a careful selection of system elements (lens, detector, etc.) and the system parameter optimization, we can influence the system performance.

To further prove the value of the MTF analysis, future efforts will be made to include in the calculations the effects of other system elements such as focus, jitter, and image processing MTFs. It is expected this will provide better matching of measured and calculated MTF results as well as give some additional direction for further EO system optimization.

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ФУНКЦИЯ МОДУЛЯЦИИ ПЕРЕДАЧИ ПРИ АНАЛИЗЕ ЭЛЕКТРООПТИЧЕСКИХ СИСТЕМ

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РУБРИКА ГРНТИ: 47.00.00 ЭЛЕКТРОНИКА. РАДИОТЕХНИКА;
47.57.00 Инфракрасная техника,
47.57.29 Приборы ночного видения.
27.00.00 МАТЕМАТИКА;
27.35.00 Математические модели естественных наук и технических наук. Уравнения математической физики,
27.35.47 Уравнения переноса.

ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Функция модуляции передачи (MTF) является полезным инструментом для анализа эффективности системы формирования изображений. Она используется при разработке электрооптических систем (ЕО), проверке целевых параметров системы, а также в задачах оптимизации тестируемой системы. Данная методология основана на теории линейных систем и обеспечивает возможность разделения анализа эффективности сложных систем ЭО на подсистемы. В настоящей статье представлена и объяснена методология MTF, а также приведены примеры измерений, произведенных в электрооптической лаборатории. Измерения MTF проводились с помощью трех видов камер в разных спектральных диапазонах, после чего результаты сравнивались с прогнозируемыми моделями и теоретическими пределами системы формирования изображения.

Методы: Лабораторные измерения и теоретическая математическая статистика.

Результаты: Результаты измерений были дополнительно проанализированы на основании проведенных лабораторных и теоретических результатов.

Выводы: Проведенные измерения показали, что рассчитанная предельная частота и кривая MTF представляют собой границу реальных измеренных характеристик эффективности системы. Таким образом, исследование подтвердило, что MTF может способствовать выявлению системных ограничений и узких мест, а также повышению общей эффективности системы. Разработаны рекомендации по дальнейшей оптимизации систем формирования изображений.

Ключевые слова: функция модуляции передачи, тестовая цель USAF 1951, электрооптика.

МОДУЛАЦИОНА ФУНКЦИЈА ПРЕНОСА У АНАЛИЗИ ПЕРФОРМАНСИ ЕЛЕКТРООПТИЧКИХ СИСТЕМА

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ОБЛАСТ: електрооптика, електроника, математика
ВРСТА ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: Модулациона функција преноса (MTF) користан је алат за анализу перформанси система за обраду слике. Користи се у дизајнирању електрооптичких (ЕО) система, при провери циљаних параметара система, али и у задацима оптимизације тестираних система. Ова методологија, заснована на теорији линеарних система, омогућава да се анализа перформанси сложених ЕО система подели на подсистеме. MTF методологија најпре је представљена и објашњена, а затим је приказано мерење извршено у електрооптичкој лабораторији. MTF мерења изведена су на три типа камера, у различитим спектралним опсезима, након чега су резултати упоређени са очекиваним моделима и теоријским ограничењима система за обраду слике.

Методе: Лабораторијска мерења и теоријска математичка израчунавања.

Резултати: На основу лабораторијских и теоријских резултата додатно су анализирани резултати мерења.

Закључак: Мерења су доказала да израчуната гранична фреквенција и кривуља MTF представљају границу за стварне перформансе система. Потврђено је да MTF може бити погодан за проналажење ограничења и уских грла система, као и за побољшање укупних перформанси система.

Кључне речи: модулациона функција преноса, тестна мета УСАФ 1951, електрооптика.

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