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Improved analytical modulation transfer function for image intensified charge coupled devices

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Abstract

The basic problem of simulation and modeling of Image Intensified Charge Coupled Device (ICCD) is the difference between the analytical Modulation Transfer Function (MTF) formulation used in the model and the experimentally obtained MTF. An investigation into the MTF of ICCD sub-components reveal that the MTF of the Image Intensifier Tube (IIT) is the main factor in this deviation.

In this study, a regulation factor for the MTF of 3^{rd} generation IITs has been developed. A commonly used MTF formulation for IITs has been modified to include a regulation factor which has helped produce more precise MTF values for the Night Vision Sight (NVS) device. The results obtained through the new formulation have been compared with the experimental results and it is revealed that the proposed formulation yields MTF values within 3% of the experimental results, on average, while the most commonly used formulation produces approximately 29.5% difference, which amounts to almost 10% improvement in analytical analysis. The analysis is then extended to other generations of IITs where similar improvements have been achieved.

Key Words: *Image intensified charge coupled device (ICCD), image intensified tube, modulation transfer function, simulation.*

1. Introduction

How well an optical system performs is usually considered a function of their ability to discern the smallest object from the farthest distance. Military specifications specify the Minimum Resolvable Contrast (MRC) and/or Minimum Resolvable Temperature Difference (MRTD) as the most important criteria for optical systems and environmental conditions (night, etc.), and thus determines the lower limits for the user to measure the aforementioned system parameters. On the other hand, the Modulation Transfer Function (MTF), expressed

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as line pairs/mm (lp/mm) or cycles/mrad, is a measure of system response in terms of spatial frequency and is probably the best measure of performance (MoP) for such systems. MTF of an optical system is a measure of its ability to transfer contrast at a particular resolution level from the object to the image. In other words, MTF is a way to incorporate resolution and contrast into a single specification. From a visual standpoint, high values of MTF correspond to good visibility, and low values to poor visibility. But this quality of visibility depends on frequency. Perhaps an easy way to interpret MTF is by thinking of imaging a target with black and white lines, i.e. a target with 100% contrast. It is a known fact that no optical system at any resolution can fully transfer this contrast to the image due to the diffraction limit [1]. In fact, as the line spacing on the target is decreased, i.e., the frequency increases, it becomes increasingly difficult for the optical system to efficiently transfer this contrast. Therefore, as the frequency increases, contrast of the image decreases and an MTF graph, which relates the fraction of transferred contrast as a function of the line frequency, is the best way to observe such performance degradation.

However, while the MTF is such an important aid to objective evaluation of the image-forming capability of optical systems, it is usually obtained experimentally, thus, leaving researchers without an analytical solution in terms of measuring the performance [2, 3]. Although there are many analytical MTF expressions proposed for optical systems, they usually do not completely fit experimentally obtained data. Accuracy of commercial MTF measurement systems ranges from 5% to 10% in absolute MTF, however obtaining accuracy to within 1% is also possible [4]. Thus, existence of an analytical expression that better fits the experimentally obtained MTF, would help researcher/manufacturers better determine the image quality of the optical system at the design phase. This is rather important as analytical expressions are employed at the modeling stage of systems and modeling is a powerful tool to gain insight into the expected performance of systems at the beginning without having to build the whole system. Hence, a less accurate mathematical model will produce reduced expectations in terms of system performance. Moreover, there are systems for training purposes that simulate the actual system functionality without having the system itself. Such systems rely on accurate mathematical models of the system and analytical expressions that result in less accurate mathematical model will lead to a training system with degraded performance.

In this study the analytical MTF formulation presented in [5] for an OMNI series 3^{rd} generation IIT has been modified to better fit the experimental results given in Military standards [6]. The resulting analytical expression has been utilized to come up with an analytical MTF formulation for an ICCD for comparison purposes as the MTF data for an ICCD employing a 3^{rd} generation night vision sight device was available. This study has also extended the analysis (see Appendix) to other generations of IIT in terms of analytical MTF formulation in order to demonstrate that similar approach could be adopted for all generations of IIT [7, 8].

2. Modulation transfer function analysis

The Modulation Transfer Function (MTF), describing the resolution and performance of an optical system is the ratio of relative image contrast divided by relative object contrast. When an object is observed through an optical system, the resulting image will be somewhat degraded due to inevitable aberrations and diffraction phenomena. Aberration is the loss of image in an optical system when the system fails to focus the incoming beams properly. Diffraction is another type of image loss caused by reflections and deviations of the light beams at transition points. While it is possible to prevent aberration by means of using appropriate optical techniques, due to the natural structure of light, even with the optical systems designed in the best way possible, it is not possible to totally eliminate the effect of diffraction. Hence, it is said that all optical systems are diffraction-limited [3]. Moreover, real optical systems will not fully conform to the design data. Manufacturing errors, assembly and alignment errors in the optics will deteriorate the overall imaging performance of the system [3]. As a result, in the image, bright highlights will not appear as bright as they do in the object, and dark or shadowed areas will not be as black as those observed in the original patterns. In general a target can be defined by its spatial frequency (number of bright and dark areas per millimeter) and the contrast (the apparent difference in brightness between bright and dark areas of the image). Performance measurement of any diffraction-limited system is carried out by sensing a test object (usually a square, triple bar pattern) through the optical/electro-optical system. Effects of diffraction on contrast with respect to the increasing frequency is given in Figure 1.

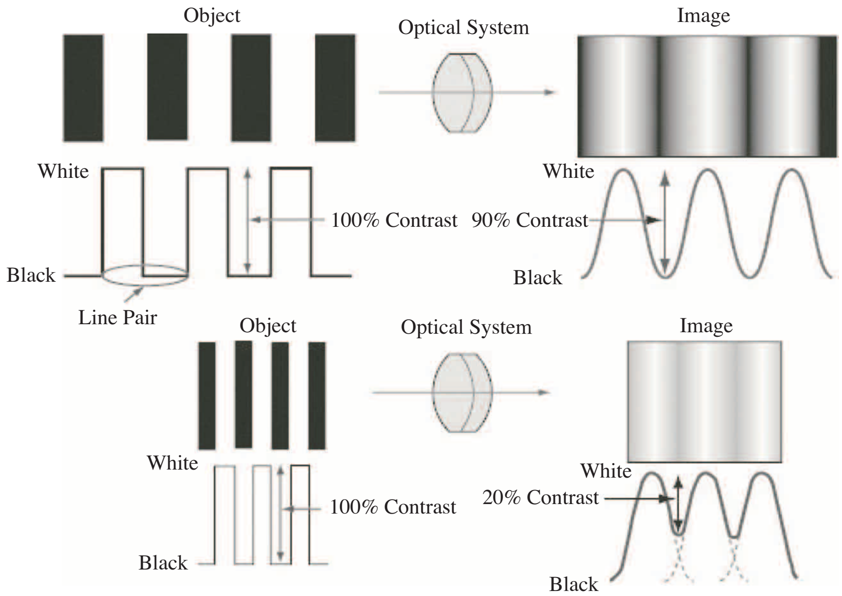

Figure 1. Effects of diffraction on the amount of contrast as the frequency is increased.

In an electrical system, general information about a circuit can be obtained from its frequency response (i.e., transfer function). Similarly, in an electro-optical system, general information about the system could also be extracted from its spatial frequency response. If the distance between consecutive target peak values is N (in millimeters), then the spatial frequency of the target is given by

$$R = 1/N \tag{1}$$

This term has units of line pairs per millimeter (lp/mm) in resolving cards. In afocal systems, generally, it is more common to use units of cycles/mrad. An afocal system is one in which the object or image is at infinity. Definition of the modulation in optical systems is as follows [4].

$$\text{Modulation } = \frac{B_{\max} - B_{\min}}{B_{\max} + B_{\min}} \tag{2}$$

where, $B_{\min}$ and $B_{\max}$ denote values of minimum and maximum amplitude, respectively, as illustrated in Figure 2.

By convention, the modulation transfer function is normalized to unity at zero spatial frequency. For low spatial frequencies, the modulation transfer function is close to 1 (i.e. 100%) and generally falls as the spatial frequency increases until it reaches zero. The contrast values are lower for higher spatial frequencies as shown in Figure 1. When the contrast value reaches zero, the image becomes a uniform shade of grey.

The intersection of the modulation function and the minimum acceptable modulation gives the "resolution power limit" as shown in Figure 3. The minimum acceptable modulation level is also known as detection threshold or noise equivalent modulation level. In some cases resolution limit, on its own, is not adequate to determine the performance of a system. In Figure 3, systems A and B have the same resolution power, but system A will produce a better image because the contrast of A at the lower frequencies is better.

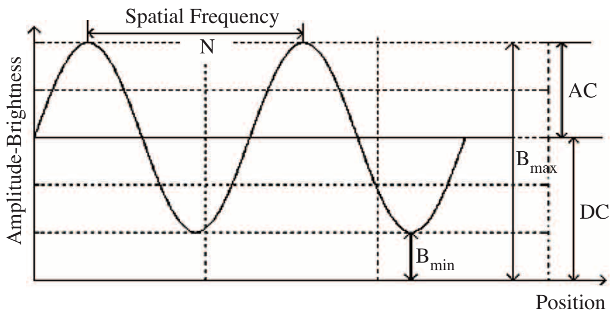

Figure 2. Concept of modulation.

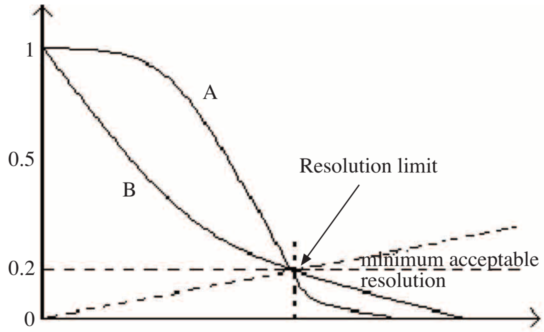

Figure 3. Two different MTFs with the same resolution limit.

3. Regulating the IIT's MTF

Image intensifier devices are electronic devices that sense low-intensity optical light, and convert it to a visible image. As shown in Figure 4, the IIT consists of a photocathode, an ion barrier film, a micro-channel plate and a phosphor screen. Low intensity photons originating from the object of interest, on passing through on objective lens, reach the photocathode. The photocathode converts the photons into electrons. The photocathode is wavelength sensitive, depending on the selected material; in this work, it operates at around 600–900 nm in 3^{rd} generation devices. The photocathode is followed by a micro-channel plate where the photoelectrons are amplified. The plate resembles a very thin glass plate and consists of millions of glass capillaries ($\sim$2 million channels). Passing through the micro-channel plate with increased gain, electrons subsequently land on the phosphor screen. The screen is phosphor-coated, which radiates under the high-energy electron irradiation and, in turn, produces a visible image of the interested object.

A generally accepted MTF formulation for an IIT is given by [5]

$$MTF_{\mathrm{IIT}}(f_x) = e^{-2\pi^2\sigma_{\mathrm{IIT}}^2 f_x^2}, \tag{3}$$

where σ_{IIT} is the 1/e spot size of the IIT and f_x is the spatial frequency in lp/mm. Spot size is related to the sensitivity of the tube and components of the system (microchannel width, phosphor screen material and voltage gain). In general, the spot size is not given and has to be calculated. The spot size of the IIT utilized in this study (OMNI-III, 18 mm, GEN III) has been calculated as approximately 15 μm.

Table 1 displays the calculated MTF values of the 3^{rd} generation IIT employed in this study for varying spot sizes (σ_{IIT}) and spatial frequencies whereas Table 2 presents the measured[1] and calculated MTF values at the reference spot size of $\sigma = 15$ μm for OMNI-III IIT in order to highlight the difference between the calculated MTF through the common analytical expression i.e., equation (3) and the measured MTF.

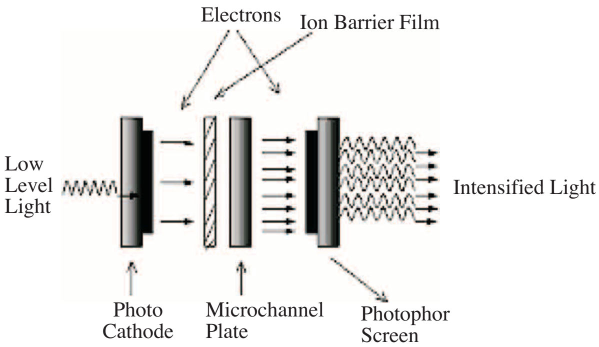

Figure 4. Intensifying light in an image intensifier tube.

Table 1. Calculated MTF value of an OMNI-III series IIT using equation (3).

	MTF Values							
σ_{IIT} (μm)	10	15	16	17	18	19	20	25
$f_x = 0$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
$f_x = 2.5$	0.9877	0.9726	0.9689	0.9650	0.9608	0.9564	0.9518	0.9258
$f_x = 7.5$	0.8949	0.7789	0.7526	0.7255	0.6979	0.6698	0.6414	0.4996
$f_x = 15$	0.6414	0.3681	0.3208	0.2771	0.2372	0.2012	0.1692	0.0623
$f_x = 25$	0.2912	0.0623	0.0425	0.0283	0.0184	0.0116	0.0072	0.0004

Table 2. Measured MTF values for OMNI-III IIT and calculated data through equation (3).

Spatial Freq. (lp/mm)	Measured MTF	Calculated MTF	Difference
$f_x = 0$	1.00	1.00	0
$f_x = 2.5$	0.83	0.9726	−0.1426
$f_x = 7.5$	0.60	0.7789	−0.1789
$f_x = 15$	0.380	0.3681	+ 0.0119
$f_x = 25$	0.20	0.0623	+ 0.1377

Figure 5 displays the MTF plots of an IIT for varying spot size, values ranging from 10 μm to 25 μm, along with the measured MTF at the spot size value of 15 μm.

[1]Measured MTF values are taken from MIL-I-49453 06 November 1989 as well as from manufacturer performance data sheet for OMNI-III series IIT.

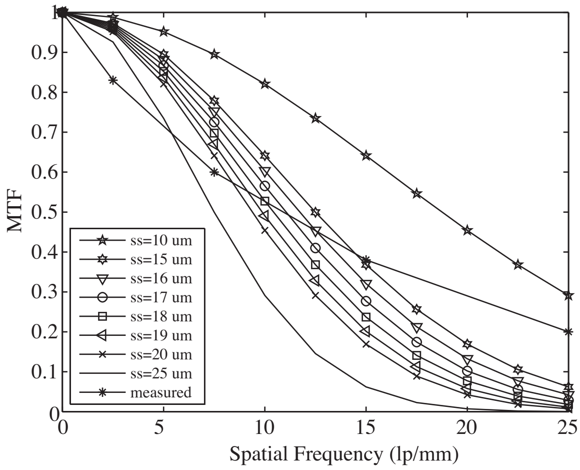

Figure 5. MTF (without regulation) of OMNI-III, 18 mm, GEN III IIT for varying spot sizes (ss) and measured MTF.

Figure 5 reveals that the original IIT MTF formulation given by equation (3) produces higher MTF for low frequencies and lower MTF for high frequencies in comparison to the measured MTF. Intuitively, such an outcome calls for a logarithmic two-piece regulation around a crossover frequency. Moreover, it is clear from Figure 5 that the measured MTF value for the spot size value of 15 μm intersects the calculated MTF for the same spot size at the spatial frequency value of 14.5 lp/mm. Since spatial frequency is given as integer numbers, 15 lp/mm could be chosen as the crossover frequency (f_{co}). Please note that since MTF is monotonic, a single term regulation factor would yield a good fit to the measured data before/after the crossover frequency while worsening the fit after/before it.

Considering the fact that the outcome of the analytical MTF formulation needs to produce decreased (increased) MTF values at lower (higher) frequencies, a regulation factor given by equation (4) has been proposed for a better fit.

$$K(f_x) = \begin{cases} 0.01\pi f_x \ln\left(\frac{f_x}{f_{co}}\right), & f_x < f_{co} \\ \\ 0.01 f_x \ln\left(\frac{f_x}{f_{co}}\right), & f_{co} \le f_x \le f_{\text{cutoff}} \end{cases} \quad (4)$$

where f_{cutoff} is 25 lp/mm[2].

Then the regulated analytical MTF for OMNI-III IITs is obtained by adding the regulation factor given by equation (4) to equation (3). The resulting MTF is then given by the following equation:

$$MTF_{\text{IIT}_{\text{reg}}}(f_x) = \begin{cases} e^{-2\pi^2\sigma_{\text{IIT}}^2 f_x^2} + 0.01\pi f_x \ln\left(\frac{f_x}{f_{co}}\right), & f_x < f_{co} \\ \\ e^{-2\pi^2\sigma_{\text{IIT}}^2 f_x^2} + 0.01 f_x \ln\left(\frac{f_x}{f_{co}}\right), & f_{co} \le f_x \le f_{\text{cutoff}} \end{cases} \quad (5)$$

The MTF values calculated through equation (5) at varying spatial frequencies for the reference spot size of $\sigma = 15\mu$m, are checked against the experimental data. The results are shown in Table (3).

[2] In Military Specifications MIL-I-49453 06 November 1989 and MIL-PRF-49040F 04 March 1999, etc. MTF's spatial frequencies usually are 2.5, 7.5, 15 lp/mm, the upper limit frequency 25 lp/mm is showed the Group 4 in the USAF 1951 Bar Target Chart and it's enough for implementation of the sensor model as seen in [9].

Table 3. Measured MTF_{15} values for OMNI-III IIT and calculated data by equation (3).

Spatial Freq. (lp/mm)	Given MTF (Measured)	Calculated MTF (with regulation) ($\sigma_{\mathrm{IIT}} = 15\ \mu$m)	Difference
$f_x = 0$	1.00	1.00	0
$f_x = 2.5$	0.83	0.8319	−0.0019
$f_x = 7.5$	0.60	0.6156	−0.0156
$f_x = 15$	0.380	0.3681	+0.0119
$f_x = 25$	0.20	0.1900	+0.0100

As it can be seen in Table (3), the measured MTF formulation improves the accuracy of the analytical formulation by producing results closer to the experimental data.

Figure 6 displays the MTF plots obtained utilizing equation (5), and it is clearly seen that unlike the plots shown in Figure 5, the plot given in Figure 6 is very close to the measured MTF plot both in shape and value for the system spot size of 15 μm. This increase in accuracy that is obtained by the proposed modification to the most common analytical expression will help manufacturers observe image quality closer to the design expectations.

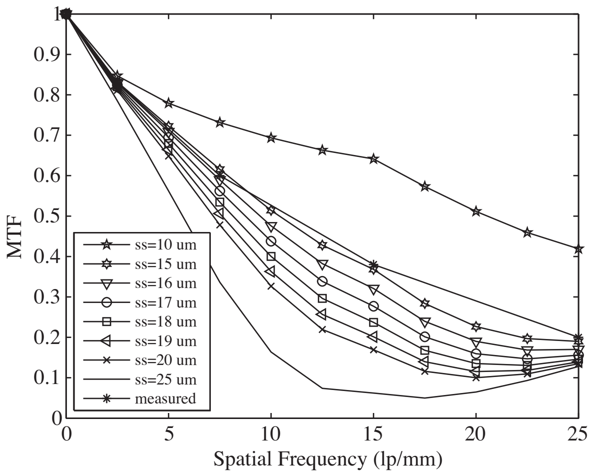

Figure 6. MTF (with regulation) of OMNI-III, 18 mm, GEN III IIT for varying spot sizes (ss) and the measured MTF.

4. Regulated MTF Applied to ICCD

An IIT is a device that amplifies the light at its entrance and in turn produces output light of sufficient intensity to make it visible. One such system that produces images at low light levels is called the Image Intensified Charged Coupled Device (ICCD) and is composed of suitable optics, the IIT, CCD and a screen. Resolution characterization defined by MTF is in terms of one-dimensional spatial frequency response, while in reality images are two-dimensional, and the use of one-dimensional frequency responses implies that spatial responses are independent functions of x and y. Moreover, the assumption of linearity implies that MTF of an optical system could be obtained by multiplying the MTFs of individual subsystems that form the whole system [5]. Thus, the analytical expression for the MTF of ICCD is

$$MTF_{ICCD} = MTF_{\text{optics}} \cdot MTF_{\text{IIT}} \cdot MTF_{CCD} \cdot MTF_{\text{screen}} \quad (6)$$

$$MTF_{\text{ICCD}} = \left[1 - \frac{4}{\pi}\left(\frac{f_x \lambda}{D_0}\right)\right] \cdot \left[e^{-2\pi^2\sigma^2 f_x^2} + K(f_x)\right] \cdot \left[\frac{\sin(\pi \cdot d_H \cdot f_x)}{\pi \cdot d_H \cdot f_x}\right] \cdot \left[e^{-2\pi^2\left(\frac{N \cdot d \cdot f_x}{2.35NTV}\right)^2}\right] \quad (7)$$

where D_0 is the aperture diameter (mm), λ is the radiation wavelength (mm), d_H is the detector size in the horizontal direction (mm), N is the number of detectors, d is the detector size (mm) and NTV is the display resolution (expressed as Television Lines per Picture Height, or TVL/Ph) [5].

As pointed out earlier, some approximate analytical expressions for optical systems are readily available. However, these expressions provide only a rough estimate of the actual, i.e., experimentally obtained MTF. ICCD, being a modern electro-optical system, is unfortunately no exception and the proposed analytical formulation for ICCD devices could only be confirmed through comparison with measured values. Thus, MTF of an ICCD is analyzed in order to demonstrate that the proposed regulation to the IIT's analytical MTF expression also improves the MTF of an optical system which comprises the IIT as a subcomponent. It is shown that, when the proposed MTF formulation for IITs is utilized, the resulting analytical MTF expression for the ICCD produces closer MTF values to the experimentally obtained MTF. Although actual MTFs or related data from hi-tech optical systems is not commonly revealed, one experimentally obtained MTF of an ICCD was published in the September 1995 issue of Laser Focus World magazine [10]. This MTF has provided the means for comparing experimental and the newly produced analytical MTFs for an ICCD. Figure 7 depicts both the experimental MTF and the analytical solution given by equation (7).

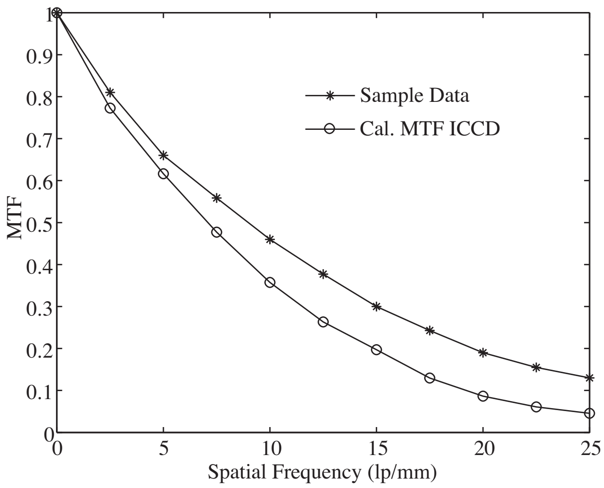

Figure 7. Analytically calculated ICCD MTF values with regulation versus the sample ICCD MTF.

As it can be clearly seen in Figure 7, the MTF obtained using (5) the analytical solution is very close to the measured MTF, up to 25 lp/mm. The proposed modification produces better results for lower frequencies as the fit worsens with the increasing spatial frequency. Nevertheless, when analyzed for the whole frequency spectrum up to the cut-off frequency, the proposed analytical expression yields MTF values within 3% of the experimental results on average.

5. Conclusions

In this study, a regulation factor to model the analytical MTF of 3^{rd} generation image intensifier tubes has been proposed. The most commonly used MTF formulation of IIT devices has been modified by employing a regulation factor which has helped MTF formulation of the NVS device and produce much more precise results, i.e., approaching those obtained experimentally. The results obtained through the formulation are compared with the experimental results and it has been observed that the proposed formulation yields MTF values within 3% of the experimental results on average in comparison to the 29.5% difference obtained with the expression without regulation.

Also, the addition of the regulation factor to the IIT's MTF has also been tested when it is used as a part of an optical system, namely, an ICCD. With the proposed analytical formulation MTF ICCD cameras could be analytically determined with more accuracy without resorting to experimental means for spatial frequencies up to 25 lp/mm. The analysis is extended to other generations of IITs, results of which are given in the appendix.

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Appendix

In this appendix the analysis given for the 3^{rd} generation IITs has been extended to other generations of IIT in order to demonstrate that similar performance achievement is possible by regulating the most commonly used analytical MTF expressions defined for IITs

We begin with the 1^{st} generation IITs. The regulated MTF expression for a 1^{st} generation IIT, given below by equation (A1) is obtained after a similar analysis described for the 3^{rd} generation IIT. The regulation factor is added to the commonly used MTF expression for IITs:

$$MTF_{\mathrm{IIT}_{reg}}(f_x) = \begin{cases} e^{-2\pi^2\sigma_{\mathrm{IIT}}^2 f_x^2} + 0.0065\pi f_x \ln\left(\frac{f_x}{f_{co}}\right), & f_x < f_{co} \\ e^{-2\pi^2\sigma_{\mathrm{IIT}}^2 f_x^2} + 0.0035 f_x \ln\left(\frac{f_x}{f_{co}}\right), & f_{co} \le f_x \le f_{\mathrm{cutoff}} \end{cases} \qquad (A1)$$

Here, the crossover (f_{co}) and cut-off (f_{cutoff}) frequencies are the same as the 3^{rd} generation IIT and the spot size has been calculated as 18 μm. Figure A1 displays the experimental (measured) and calculated MTF values with regulation for a 1^{st} generation IIT.

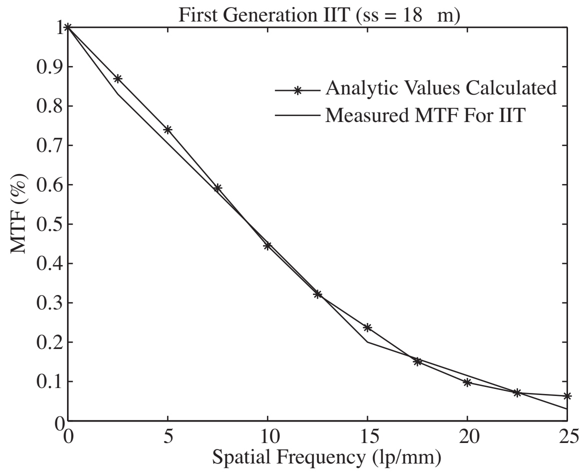

Figure A1. Comparison of calculated 'MTF with regulation' to the measured MTF for OMNI-I IIT.

When a similar analysis is carried out for the 2^{nd} generation IIT the following modified MTF expression with regulation is obtained:

$$MTF_{\mathrm{IIT}_{reg}}(f_x) = \begin{cases} e^{-2\pi^2\sigma_{\mathrm{IIT}}^2 f_x^2} + 0.006\pi f_x \ln\left(\frac{f_x}{f_{co}}\right), & f_x < f_{co} \\ e^{-2\pi^2\sigma_{\mathrm{IIT}}^2 f_x^2} + 0.01 f_x \ln\left(\frac{f_x}{f_{co}}\right), & f_{co} \le f_x \le f_{\mathrm{cutoff}}. \end{cases} \qquad (A2)$$

The system spot size for this analysis has been calculated as 18 μm and the crossover (f_{co}) and cut-off (f_{cutoff}) frequencies are the same as the 3^{rd} generation IIT. Figure A2 displays the experimental[3] and calculated MTF values with regulation for a 2^{nd} generation IIT.

[3]MIL-PRF-49428 (CR) Aviator's Night Vision Imaging System AN/AVS-6(V) 25 September 1995

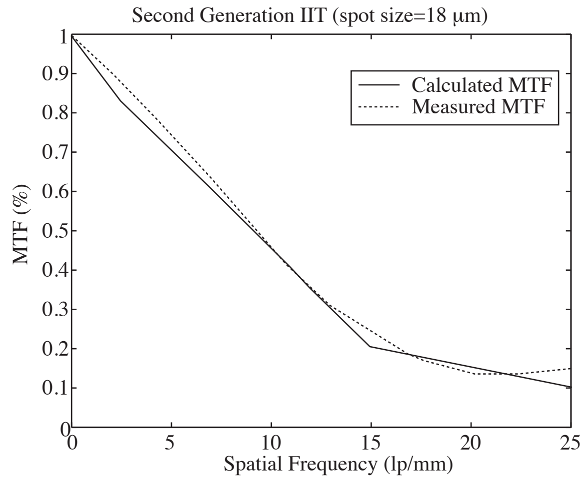

Figure A2. Comparison of calculated MTF with regulation to the measured MTF for OMNI-II IIT.

The proposed analytical MTF expression for the 4^{th} generation IITs is given by following equation where the regulation factor is added to the IITs MTF expression:

$$MTF_{\mathrm{IIT}_{reg}}(f_x) = \begin{cases} e^{-2\pi^2\sigma^2_{\mathrm{IIT}}f_x^2} + 0.0055\pi\, f_x \ln\left(\frac{f_x}{f_{co}}\right), & f_x < f_{co} \\ e^{-2\pi^2\sigma^2_{\mathrm{IIT}}f_x^2} + 0.01 f_x \ln\left(\frac{f_x}{f_{co}}\right), & f_{co} \le f_x \le f_{\mathrm{cutoff}}, \end{cases} \quad \text{(A3)}$$

where, the crossover (f_{co}) and cut-off (f_{cutoff}) frequencies are the same as the 1^{st}, 2^{nd} and 3^{rd} generation IITs, namely, 15 lp/mm and 25 lp/mm, respectively. The calculated spot size for the 4^{th} generation IIT is 10 μm. Both the regulated MTF and measured MTF values[3] for OMNI-IV IIT is displayed in Figure A3.

The proposed analytical expressions for the 1^{st}, 2^{nd} and 4^{th} generation IITs produce even better accuracies than we achieved for the 3^{rd} generation IIT. The proposed modification to the 1^{st}, 2^{nd} and 4^{th} generation IIT analytical MTF expressions yields MTF values within 1% of the experimental results on average.

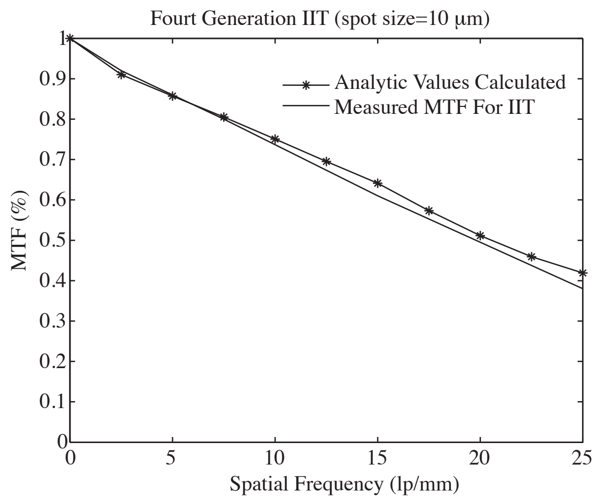

Figure A3. Comparison of calculated MTF with regulation to the measured MTF for OMNI-IV IIT.