Optica Applicata, Vol. LIV, No. 2, 2024
DOI: 10.37190/oa240203

Subjective measurement of resolution of image intensifier tubes

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Limiting resolution is traditionally defined as a spatial frequency of smallest resolvable element of a resolution target that can be distinguish by a human observer. This definition and measurement method have been criticized in a series of literature sources due to its subjectivity and low repeatability/accuracy. Such criticism looks reasonable as it is commonly known that results of measurement of resolution of the same tubes carried out by several test teams can differ significantly. This paper presents a detail analysis of classical subjective measurement method of limiting resolution of image intensifier tubes implemented by real test systems. The findings show that in spite of a common opinion, subjectivity of measurement is not the main reason for differences of test results carried out by different test teams. The main reasons are differences in performance of optics of test systems, use of resolution targets of different types and polarity, and inherent spatial non-uniformity of performance of image intensifier tubes. The paper also shows that due to spatial non-uniformity it is very difficult to design automatic test systems that could produce the same results as human observers using classical subjective measurement method.

Keywords: image intensifier, IIT, resolution, subjectivity.

1. Introduction

Image intensifier tubes (IITs) are vacuum tubes that amplify a non-detectable (or barely seen) image at their photocathodes to a high-light level, clearly seen image created at the screen plane. The incoming light is converted into photoelectrons by photocathode of the tube. Next, highly intensified photoelectrons strike the phosphor screen (anode) and a bright image is created that human can easily see. IITs are the most important blocks of night vision devices used worldwide in military, security and civilian applications.

Resolution of IITs is a subjective parameter. It gives information about IIT ability to produce detailed output images of observed scenery to be analysed by human observer. In this way, higher resolution IITs allow operators of night vision device to better discriminate different aspects of the observed scenery like: to detect a point source, to detect small objects against a plain background, to resolve two or more objects that are very close, to distinguish discontinuities or irregularities in object contours, *etc*.

At present there are no international standards that regulate testing IITs. At the same time, most of IITs are used for military applications. Therefore, it cannot be surprising that resolution of IITs is typically measured all over the word by test teams that claim to be using recommendations from a series of US military MIL standards [1-4]. However, in spite of this apparent universal acceptance of recommendations of MIL standards, it is a common situation that measurement results of resolution of the same IIT tested by different test centres in different countries can differ quite significantly.

This paper presents a detail analysis of classical subjective measurement method of resolution of IITs implemented by real test systems. The findings show that in spite of a common opinion, subjectivity of measurement is not the main reason of poor accuracy/repeatability of measurement of resolution by different test teams.

2. Classical measurement method

According to US MIL standards there are two main types of resolution: limiting resolution and high level (bright-light) resolution. The first one gives information on IIT performance at typical nigh level light conditions, when the second one gives information on performance under non-typical high level (day level) illumination. Since limiting resolution is considered as more important, this paper focuses on its measurement, but the majority of discussion is also valid for high light level resolution. Therefore, the term resolution should be understand as limiting resolution, unless stated otherwise.

The limiting resolution is commonly considered as one of the two most important parameters of IIT, because it is used to calculate figure of merit (FOM – main criterion for evaluation of IITs). FOM is calculated as a product of limiting resolution and signal -to-noise ratio (SNR). It is a parameter that is present in practically every data sheet of image intensifier tubes [5-8].

In detail, the limiting resolution is defined as the smallest pattern of the United States Air Force (USAF) 1951 Resolving Power Test Target (Fig. 1) for which the ob-

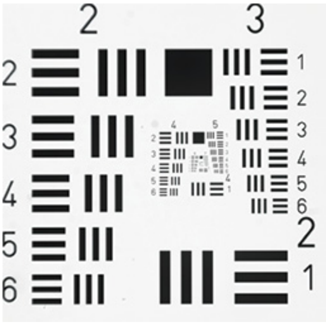

Fig. 1. USAF1951 resolution target (groups 2-8).

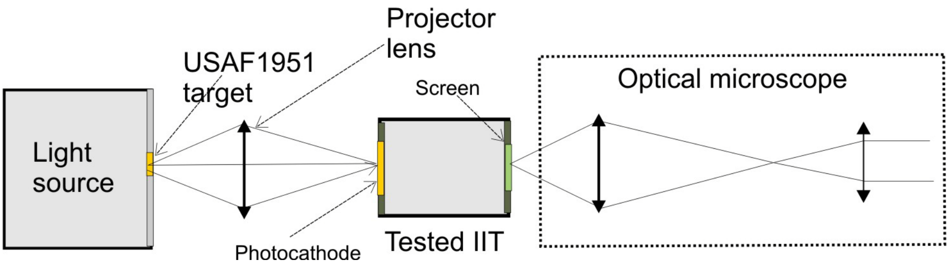

Fig. 2. Graphical concept of a system for measurement resolution of IITs according to MIL standards.

server can distinguish three black lines and the clear areas between the black lines, for both the vertical and horizontal direction [9]. Technical details of USAF1951 target can be found at [10]. It is not directly written but a user is allowed to regulate illumination level to achieve best results.

MIL standards recommend measurement of the limiting resolution using four block test system [1-4] (Fig. 2):

1. Light source,
2. USAF1951 resolution target,
3. Image projector lens,
4. 10× power magnifier (option: high power microscope).

The first block is a uniform light source of 2856 K colour temperature. Its task is to irradiate input plane of the image projector. The second block is the USAF1951 resolution target. The third block is a projecting lens capable of projecting image of the resolution target on photocathode of the tested tube. The fourth block is the power magnifier lens used to magnify image of the resolution target created at the tube screen.

The measurement of resolution is to be done by projecting image of USAF1951 target on photocathode of tested IIT and by subjective analysis of image at the screen of this IIT by a human observer using the 10× power magnifier.

The old MIL standards recommend the use of a simple 10× power magnifier [1-4]. This low magnification lens was enough to enable measurement of resolution of IITs say 5 decades ago (resolution at level below 30 lp/mm) but cannot enable accurate measurement of resolution nowadays (resolution at level over 80 lp/mm). However, according to newest interpretation of US military authorities, the use of high power microscopes is allowed [11]. It is also clarified that resolution is a measure of performance of IIT alone and should not be influenced by limitations of the test system or the sight of the observer. Practically it means that it is recommended to use near perfect test system having negligible influence on measurement results.

Subjective definition and measurement method of resolution have been criticized in a series of literature sources on arguments of subjectivity and low repeatability/accuracy [12-14]. These supposed drawbacks of classical measurement method have generated interest in automatic measurement systems. Reports on development of a series of computerized systems for automatic measurement of resolution of IITs have been published [15-17].

There are also some literature sources that clearly indicate the relationship of limiting resolution to modulation transfer function (MTF) and the possibility to determine limiting resolution by measurement of MTF of IITs and redefine resolution based on measured MTF [18-20].

However, so far these automatic test systems are not available on international market and resolution of IITs manufactured in high numbers worldwide is measured using earlier mentioned classical subjective method. The problem is that reported earlier low repeatability/accuracy problems are still not solved. The author, who is CEO of one of manufacturers of stations for testing IITs, knows practically that it is high probability that measurement results of resolution of the same IIT, tested by different test teams, can differ significantly. Therefore, let us now discus reasons for such poor metrological situation. These reasons can be divided into six main groups:

1. Performance of optics of test systems,
2. Type/polarity of resolution target,
3. Photocathode illumination level,
4. Inherent spatial non-uniformity of IITs,
5. Human operator,
6. Rules for criterion of resolve.

3. Performance of optical channel of test system

The description of a test system needed for resolution measurement presented above shows that according to classical definition presented in MIL standards, the limiting resolution is a purely subjective parameter measured using apparently simple test system.

It is true that nowadays it is an easy task to design a well working test system of structure as shown in Fig. 2, but for testing old IITs of resolution below about 40 lp/mm manufactured several decades ago. However, it is a technical challenge to design a test system that enables accurate measurement of resolution of modern IITs of resolution as high as 100 lp/mm.

In order to enable accurate measurement of resolution, the test system must generate for the observer a near perfect image of the resolution target that is not influenced by any limitations of its design. This near perfect output image can be achieved when these two conditions are fulfilled:

1. The influence of image projector on deterioration of image quality of image of resolution target to be projected to photocathode plane is negligible;

2. The influence of magnifier block (microscope or video microscope) on deterioration of image quality of image of resolution target to be projected to eyes of the observer is negligible.

It is commonly accepted in optics that if we have a system built from two blocks, then the influence of one block on the quality of image projected by the system can be considered as negligible if resolution of this block is at least five times higher than resolution of the second block [21]. Practically it means that two detail conditions must be fulfilled:

$$v_{\text{pro}} \geq 5 \cdot v_{\text{IIT}} \tag{1}$$

$$v_{\text{mic}} \geq 5 \cdot v_{\text{IIT}} \tag{2}$$

where v_{pro} is resolution of the projector optics, v_{IIT} is resolution of the image intensifier tube, and v_{mic} is resolution of the microscope optics. This rule is valid also in optics of video microscopes that often replace classical microscopes as tools to analyse image of screen of IITs.

As we can see, the projector optics and microscope optics of resolution over 500 lp/mm are needed to enable testing modern IITs of resolution as high as 100 lp/mm. It is technically possible to design these optical systems of such a resolution but it is a challenge met by only some of test systems used worldwide. Great majority of older test systems do not fulfill the conditions (1) and (2). Therefore, it is natural that measurement of resolution of modern IITs using such old test systems will generate significantly lower results comparing to true values.

This easily predicted conclusion has been confirmed by the experiment carried out by the author in the form of measurement of resolution of several IITs using systems of different resolution using two test stations of different resolution. Recent exchange of both projection optics and microscope optics in test systems manufactured by company author is working has delivered opportunity for such experiment. Results are in Table 1.

T a b l e 1. Measurement of resolution of several IITs using test systems of different resolution.

	Resolution [lp/mm]	
	Test system of medium resolution $v_{\text{pro}} \geq 340$ lp/mm, $v_{\text{mic}} \geq 340$ lp/mm	Test system of high resolution $v_{\text{pro}} \geq 500$ lp/mm, $v_{\text{mic}} \geq 500$ lp/mm
Tube 1	59.2	59.2
Tube 2	64	64
Tube 3	80.6	83.8
Tube 4	83.8	87.1
Tube 5	87.1	97.8

4. Resolution targets

The MIL standards clearly recommend to use positive contrast (black opaque pattern on transparent bright background) USAF1951 resolution target to measure resolution of IITs. However, this target is characterized by three main drawbacks:

1. Large step of regulation of spatial frequency of patterns of USAF1951 target,
2. Low number of bars of resolution patterns of USAF195 target,
3. Noisy image seen through positive contrast USAF1951 target.

The first drawback refers to high step of change of resolution of patterns of USAF1951 target at level of 12%. This high step makes impossible to detect differences in resolution of tubes of similar performance and significantly degrade accuracy of resolution measurement.

The second drawback refers to the fact that from mathematical standpoint, tri-bar targets poorly represent square wave of a specified frequency due to the effect of windowing a periodic square wave pattern. Targets of higher number of bars fit much better.

The third drawback refers to general impression of noisiness of image of positive contrast USAF195 target during resolution measurement. This noisiness effect is strongly reduced when using negative contrast resolution targets (USAF1951 or other targets) when image is dominated by black uniform noise free area. Work with negative contrast target is more comfortable for observers.

Due to drawbacks discussed earlier, the original USAF1951 target shown in Fig. 1 is rarely used even by US manufacturers. Analysis of industrial practice shows that resolution worldwide is measured using mainly three types of resolution targets: modified USAF1951 target, modified Ronchi resolution target, GOST resolution target. Each of these targets can be manufactured in both negative and positive polarity. That gives potentially six combinations target type/polarity. Targets are shown in Fig. 3. However, practically only three such combinations are typically used:

1. Modified positive contrast USAF1951 target,
2. Negative contrast modified Ronchi resolution target,
3. Negative contrast GOST resolution target.

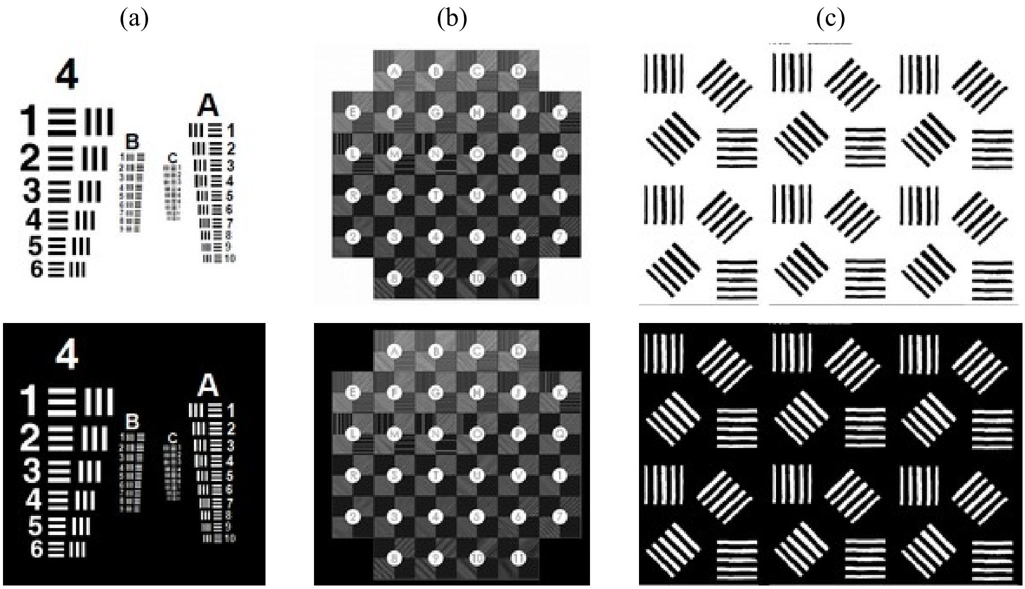

Fig. 3. Three types of resolution targets for two polarities used to measure resolution of IITs (a) USAF1951, (b) Philips, and (c) GOST.

The first one is used by US manufacturers of IITs, manufacturers of systems for testing IITs and some of non-US manufacturers. The second one is popular among EU manufacturers. The third target is mainly used by Russian manufacturers or companies having strong commercial/technical links to these manufacturers.

The main aim of modification of USAF1951 target is to minimize step of change of spatial frequency between neighbour resolution patterns in range of interest when testing image intensifier tubes from about 16 lp/mm to about 120 lp/mm. In detail, the modification is to add additional elements in between existing ones, while preserving 3:1 bars ratio. The step is often reduced to 4%. The modified patterns typically try to mimic USAF1951 spiral layout (Fig. 3(a)).

The modified USAF1951 target (Fig. 3(a)) uses patters of 3 : 1 bars ratio, and includes the patterns of spatial frequencies met in typical USAF1951 target. Modified USAF1951 targets are also typically targets of positive contrast. Therefore, it can be concluded that the modified USAF1951 fulfils recommendations of MIL standards for systems for resolution measurement. However, situation is totally different in case of two other targets.

The second, commonly used name of the modified Ronchi target is the Philips target. This name refers to non-existing French manufacturer of IITs who popularized this target. The modified Ronchi (Philips) target is a set of progressive smaller Ronchi rulings (Fig. 3(b)). For each size, there are 4 rulings, each rotated by 45°. Each target (one ruling) is approximately 0.25mm in length, giving 0.5 mm for one set. For the pattern to be considered as resolved only part of the ruling needs to be distinguished. The minimal step of change of spatial frequency is equal to 2 lp/mm.

The name GOST target refers to a target recommended by Russian GOST 15114-78 standard [22]. The same recommendations are repeated by ISO 14490 7:2016(E) standard [23].

Each group of GOST test target consists of four patterns at four different angular orientations formed by five bars each. The bars are of equal length and widths and are arranged as in Fig. 3(c).

There are two significant advantages of modified Ronchi target and GOST target over the USAF195 target (Table 2):

1. Higher number of bars of single resolution pattern,
2. Higher number of angular orientations of resolution patterns.

T a b l e 2. Comparison of main features of three types of resolution targets.

Feature	Modified positive USAF1951 target	Negative modified Ronchi target	Negative GOST target
Number of bars in a single pattern	3	Vary but typically over 12	5
Number of angular orientations of bars	Two (vertical, horizontal)	Four (vertical, horizontal, and two 45°)	As in modified Ronchi
Approximate step of change of spatial frequency	4%	2 lp/mm	6%

The main disadvantage is the fact that the differences between USAF1951 target and Philips/GOST targets are big and the use of the latter targets is clearly against recommendations of MIL standards. Therefore, the author prefers the use of modified USAF1951 target as the only solution to improve metrological situation and potentially enable comparison of results generated by different test teams. However, the reality is that all three types of resolution targets are used worldwide. In rare cases, the targets listed in Table 2 of inverse polarity are used. Therefore, the author has carried out experiments to determine the influence of type/polarity of resolution target on the value of measured resolution of IITs. The results are shown in Figs. 4 and 5.

Test results shown in Fig. 4 clearly indicate that tests using modified Ronchi target generate noticeably better results in comparison to results obtained using modified

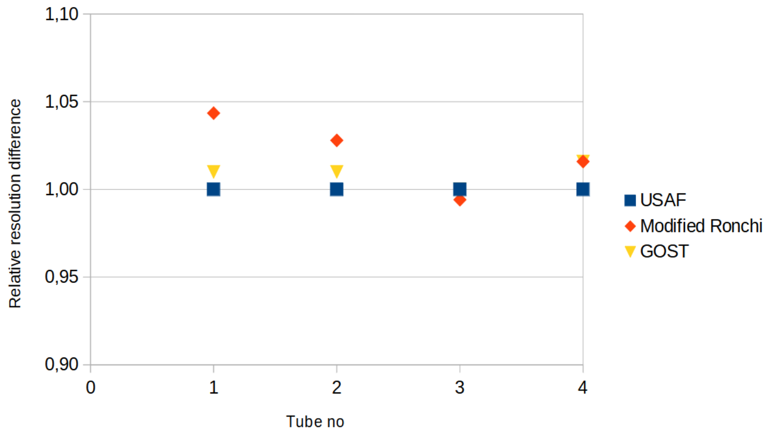

Fig. 4. Relative change of results of measurement of resolution of four IITs due to change of target type (normalization to results obtained using positive contrast USAF1951 target).

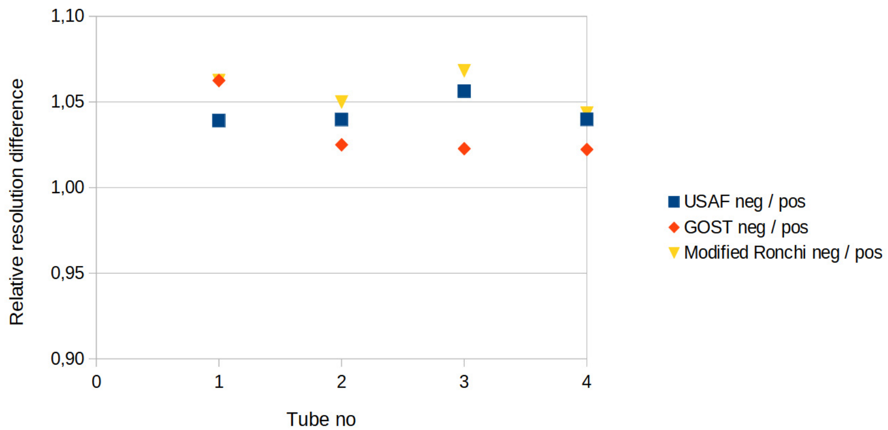

Fig. 5. Relative change of resolution measurement using different targets due to the change of target polarity (normalized to results for positive polarity).

USAF1951 target (average 3% improvement). However, tests using GOST target produce only barely noticeable improvement (about 1% improvement). This situation is probably related to the highest number of bars in resolution pattern of modified Ronchi target.

Test results shown in Fig. 5 indicate that tests using targets of negative polarity (bright patterns on black background) generate slightly better (4% improvement). This rule is valid for all three types of targets. It should be also noticed that measurement of resolution using negative polarity targets is much more comfortable for observer due to low perceived noisiness of image to be analysed.

5. Illumination level

The MIL standards allow optimization of illuminance level at photocathode plane to achieve best resolution measurement results. However, sometimes illumination level is fixed due to different techno/commercial reasons. Therefore, the author has carried out measurement of resolution at variable illuminance at range from 0.5 to 50 mlx

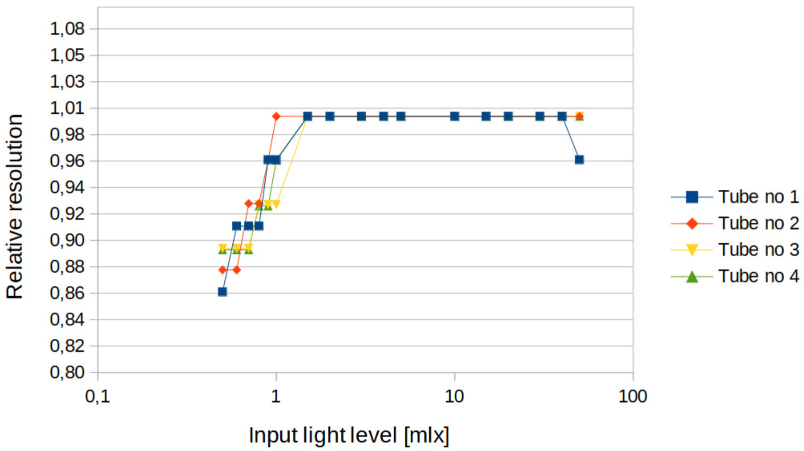

Fig. 6. Relative change of resolution measurement depending on input light level (normalization to results for 5 mlx).

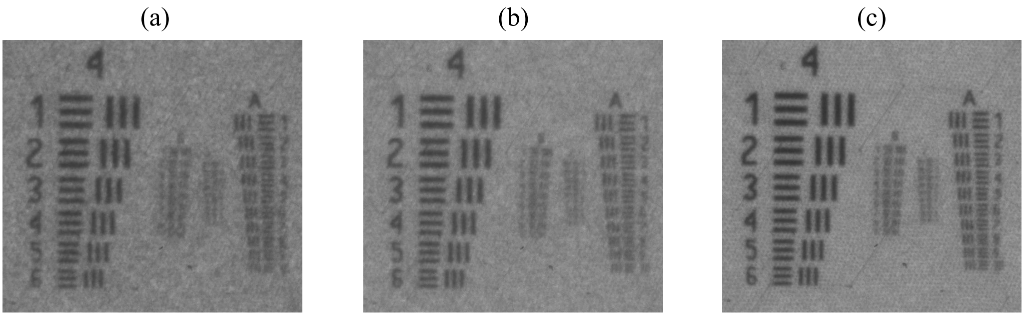

Fig. 7. Image of modified USAF1951 target at three illumination levels: (a) 0.5 mlx, (b) 1 mlx, (c) 50 mlx.

(approximately full moon/quarter moon illumination conditions) using modified USAF1951 target. The results are shown in Fig. 6. Figure 7 shows single frames from measurements at different light levels. It has been noticed that noisiness of image increases when illumination decreases. However, it has been found that there is practically no influence of illuminance level (in typical range 1 to 50 mlx) on measured resolution of tested tubes. This influence has become noticeable below about 0.7 mlx when the noise of image makes it difficult to recognize the smallest patterns, and reduces measured resolution.

6. Inherent spatial/angular non-uniformity of IITs

Performance of majority of optical devices or electro optical imagers is spatially non-uniform. The best performance is typically achieved at the centre, then image quality gradually deteriorates when increasing distance to the centre. Therefore, it is a common procedure to measure both centre resolution and peripheral resolution.

Situation with IITs is significantly different. There is still slow deterioration of image quality with distance to the centre. However, there is also a new effect: significant fast fluctuations of image quality. A small change of position of resolution pattern by a fraction of millimetre can cause a noticeable change of measured resolution. In addition, results of resolution measurement depend also on angular orientation of resolution pattern.

This inherent spatial/angular non-uniformity of performance of IITs is mainly a result of technical problems with manufacturing and later with coupling of two parts of IITs: microchannel plate MCP and output fibre optics. The first one is built in form of array of millions of hollow channels. The second one is built in form of array of millions of ultra-thin fibres. The manufacturing precision and coupling of microchannel plate MCP with output fibre optics are a huge technological challenge if we consider that diameter of both hollow channels and fibres in modern tubes of ultrahigh resolution can be as low as 4 μm.

If this manufacturing/coupling is near perfect (rare case) then image quality is relatively uniform. Measurement of resolution carried out at several positions/orientation generates almost the same results.

However, in more common case, there is a significant non-uniformity. The worst scenario is the situation when there are in output image only few spots of significantly higher image quality. Measurement at such spots will generate much better resolution result in comparison to average result. These locations are commonly called sweet spots.

In order to verify this hypothesis of spatial/angular non-uniformity of performance of IITs, the author has carried out many measurements of resolution of a series of IITs at different spatial locations and angular orientations. Later, the measured data have been analysed and two types of resolutions have been determined: maximal and mean. As we can see in Fig. 8, the ratio between the two is in range of 8% ± 2%. This can lead to two conclusions:

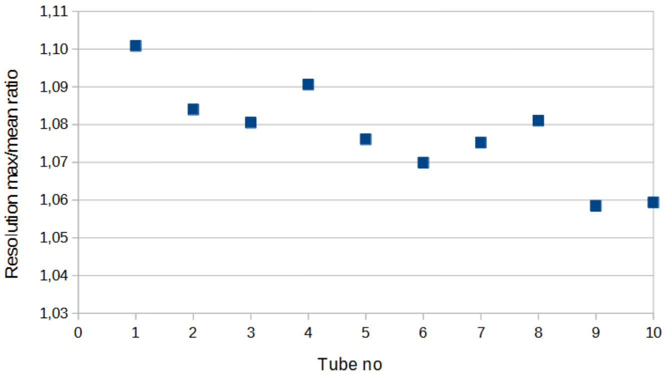

Fig. 8. Relative ratio of maximal resolution to mean resolution for a series of ten IITs.

1. Non-uniformity of IITs has a significant influence on results of measured resolution,

2. Common practice of measurement of resolution for so-called "sweet spots" generates the results that are overoptimistic.

In author's opinion, measurement of resolution at sweet spots should be forbidden because this measurement method falsify real average performance of IITs. However, the author doubts that such recommendation can be practically implemented because manufacturers are under pressure to produce IITs with high resolution and sweet spot method is a tempting solution to improve nominal performance of tested image intensifier tubes.

7. Human operator

Human operator is typically considered as the main source of low repeatability of measurement of resolution of IITs. People with vision problems are considered as totally unacceptable to work as operators. However, years of practical work in the field of testing IITs of the author indicate that this opinion is only partially true.

Human operators can be a source of variability of measurement results only if following scenarios occur:

1. Operators have non-corrected defects of vision,

2. Operators are not familiar with the work whose aim is to recognize targets in noisy images.

In author's opinion, operators with some vision problems that can be corrected using glasses/contact lenses can produce proper measurement results similar to people having no eye defects at all. However, there is always some risk due to the use of such operators and performance of such observers should be cyclically verified by comparison tests.

The second factor to be considered, when evaluating the suitability of an observer for resolution tests, is the training. The employment of inexperienced operators who are not familiar with detecting targets in noise images should be prohibited. Such observers have a tendency to generate over pessimistic results.

Finally, it is recommended to use computer simulation software that can simulate process of measurement of resolution of IITs in a repeatable way. Such software is a good way to eliminate observers that generate non-stable results, especially observers that generate overoptimistic results.

8. Rules for criterion of resolve/not resolve

It is typical that two teams of experienced operators with no eye defects shall produce different measurement results if they use different rules for resolving/not resolving resolution targets. The question is what confidence level to consider that operator of test station can resolve resolution pattern is proper.

Two possible scenarios have been analyzed:

1. The operator can see separately some parts of three bars of the resolution pattern. Confidence level: 50% probability that it is a true resolution pattern.

2. The operator can see clearly almost all parts of three bars of the resolution pattern. Confidence level: 90% probability that it is a true resolution pattern.

Experiments that have been carried under author supervision have shown that the measurement results in case of criterion no 1 can be as much as 4% better comparing to criterion no 2.

9. Limitations on automation of resolution measurement

Spatial non-uniformity of performance of image intensifier tubes discussed in Section 6 generates also a technical challenge for automation of measurement of resolution of IITs.

Measurement of resolution using a classical subjective method is typically done for so-called sweet spots. These spots are often very small and the image of resolution pattern is noisy. These two factors make it difficult to develop software capable to detect resolution patterns in such spots or to analyse the image of any reference target in such a non-uniform background. Please note that many algorithms for objective measurement of resolution are based on measurement of modulation transfer function MTF. Measurement of the latter parameter is based on image analysis of a large area in order to reduce the influence of noise. Therefore results of MTF measurement are typically over-pessimistic comparing to expected values estimated on basis of measured resolution at sweet spots.

10. Metrological recommendations

The best solution to improve metrological situation in the field of measurement of resolution of II tubes would be worldwide acceptance of updated and improved US MIL standards that regulate testing of II tubes. However, it is not known if and when such new standard can be expected. Further on, it can be doubtful if such new, even perfect standard could be accepted worldwide in situation when old US MIL standards have never been universally accepted.

In such a situation the author proposes damage-limited solution: to present in test reports not only measurement results but also detailed test conditions (target type, target polarity, photocathode illuminance, average or sweet spot result, resolution of image projector, resolution of microscope, confidence level). Presenting resolution measurement results with information on detail test conditions would enable reliable comparison of measurement results carried out by different test teams worldwide.

11. Conclusions

This paper presents a new insight on an old problem of accurate measurement of resolution of image intensifier tubes. It shows that in spite of a common opinion, the subjectivity of measurement is not the main reason for common differences of test results carried out by different test teams. The main reasons are differences in performance of optics of test systems, use of resolution targets of different types and polarity, and inherent spatial non-uniformity of performance of image intensifier tubes. The paper also shows that due to spatial non-uniformity of performance of image intensifier tubes it is very difficult to design automatic test systems that could produce the same results as human observers using classical subjective measurement method.

Acknowledgement
Research presented in this paper has been funded by a grant from the National Center for Research and Development of Poland no POIR.01.01.01-00-0173/20-00.

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Received August 26, 2023
in revised form December 17, 2023