Measuring Display System Resolution Precisely

Charles J. Lloyd
Visual Performance LLC
Ellisville, Missouri
Charles.Lloyd@VisualPerformance.us

ABSTRACT

Spatial resolution is arguably the most important determinant of display system performance. However, the simulation training industry currently uses variations of low precision subjective measures of resolution to evaluate training display systems. Furthermore, these subjective methods are not applied consistently across programs or over the life of a single training device. Meanwhile, far more precise objective measures are commonly used to specify other less-influential display system attributes such as geometry, luminance, and white point.

This paper summarizes the results of a series of papers describing the research, development, and testing of an objective metric of display system resolution designed specifically to meet the needs of the simulation training industry. This multi-year R&D effort culminated in the development of a proposed standard Metric description, Test pattern definition, and measurement Procedure (MTP) that is provided for consideration by the simulation training community. Test results indicate the standard deviation of repeated measurements made using the proposed method is 1/12th of that obtained using the current subjective methods and the correlation between the proposed and current methods is strong (R^2 = 0.79, 17 df). Multiple resolution measurements can be made across the field of view of a display system using a simple pan-tilt unit in 1/14th the time required using the current methods.

The substantial improvement in the precision of resolution measurements is expected to increase the probability that delivered systems will meet customer expectations and reduce arguments and delays during the acquisition of these complex systems. The significant improvement in measurement speed translates into the ability to make comprehensive measurements of complex display systems consistently across programs and over time.

ABOUT THE AUTHOR

Dr. Charles J. Lloyd is president of Visual Performance LLC where he addresses research and development challenges relating to complex display system requirements, metrics, and measurements. Charles has 30 years of experience in display systems and applied vision research at such organizations as Honeywell's Advanced Displays Group, The Lighting Research Center, BARCO Projection Systems, FlightSafety International, and the Air Force Research Laboratory. Charles has published more than 80 papers in this arena.

Measuring Display System Resolution Precisely

Charles J. Lloyd
Visual Performance LLC
Ellisville, Missouri
Charles.Lloyd@VisualPerformance.US

INTRODUCTION

As part of an ongoing research and development effort we have developed a **M**etric description, **T**est pattern definition, and measurement **P**rocedure (MTP) document for display system static resolution and sampling artifacts. This MTP is published here so that it can be considered for use in the simulation training industry. In this paper we compare the proposed method with current methods and provide an example of how the proposed MTP can be used to evaluate training display system performance. The development of the proposed metric began in 2010 as part of the Immersive Display Evaluation and Assessment Study (IDEAS) program (Lloyd, 2011) which was funded by the Air Force Research Laboratory (AFRL) in Mesa Arizona. The objectives of the IDEAS program included the development of requirements and objective metrics for training display systems that are defensible on the basis of training task performance. During the first year of the program two extensive human factors evaluations were completed and a predictive model of static and dynamic system resolution was developed (Lloyd, Joralman, et. al., 2011; Lloyd, Williams, and Pierce, 2011). This model was designed to predict the range at which observers can correctly discriminate distant aircraft based on display design variables such as pixel pitch, anti-aliasing, contrast, luminance, and pixel hold time (motion blur reduction).

The high predictive capability of the model derives from the use of the modulation transfer function (MTF) of the display system and the contrast threshold function (CTF) for human observers. The validity of the "perceptually-weighted" image quality metrics based on the MTF and CTF is well-established in the literature and many of these studies are summarized by Snyder (1985) and Barten (2000). These authors and their colleagues published the results of dozens of evaluations that demonstrated strong correlations between these objective measures of resolution and the performance of observers for tasks such as visual search (Snyder, Keesee, et. al., 1974), target recognition (Task, 1979) and military photo interpretation (Beaton, 1984). Lloyd et. al. went on to demonstrate high correlations with the range at which observers can discriminate distant aircraft ($R^2 = 0.91$, 199 df) and depth discrimination performance ($R^2 = 0.88$, 35 df) with stereoscopic displays (Lloyd, Williams, and Pierce, 2011; Lloyd, 2012). Currently the MTF-CTF based metrics of imaging system performance are used extensively in the fields of electro-optical imaging systems design and remote sensing and are well-described in books by Holst (2000), Boreman (2001), Vollmerhausen, et. al., (2010), and Fiete(2010).

Four years ago Lloyd and Basinger (2013) introduced a test pattern and MTF-CTF based metrics of system resolution and sampling artifact magnitude (Lloyd, 2013) that were specifically designed for evaluating display systems for simulation training applications. The method was successfully used in support of the acquisition of the KC-10 boom operator trainer (BOT) visual system upgrade that commenced in 2016. Over the past three years additional evaluations (Lloyd, 2014; Lloyd, 2015; Lloyd, 2016) of the proposed method have been completed and selected results from these efforts are described in this paper. The paper goes on to summarize the benefits and limitations of the proposed MTP.

RESOLUTION MEASUREMENTS

Current Methods

While there is significant variation in the current methods used in the simulation training industry, all involve the use of a high-contrast periodic test pattern that is subjectively evaluated by one or more observers. For example, in the world of commercial flight simulation (FAA, 1995; JAR, 2003; ICAO, 2003) resolution is evaluated using two related methods. In the first method, a horizontal string of many points of light with a regular spacing is displayed and the observer position is moved towards and away from the light points to find the distance at which the individual lights are just discernable. In the second method, a set of white-dark bars at the end of the runway are used as the observer distance is adjusted until the observer can barely discern the dark gaps between the bars.

In the military training arena resolution is measured typically using horizontal and vertical grating patterns with between 3 and 10 white bars set against a black background. The position of the grating pattern is adjusted towards and away from the observer to find the distance at which the individual bars are barely discernable. This procedure is illustrated in Figure 1 which shows photographs of the test pattern presented at five distances from the observer. In the left most panel, the test pattern is nearest the observer and each black-white cycle of the pattern spans 3.7 pixels which produces seven distinct bars. In the right most panel, the test pattern is farthest from the observer and each cycle of the pattern only spans 1.4 pixels which renders the individual bars indiscernible. The feint thin dark lines in these images are the boundaries between the display pixels which are unrelated to the bars in the test pattern.

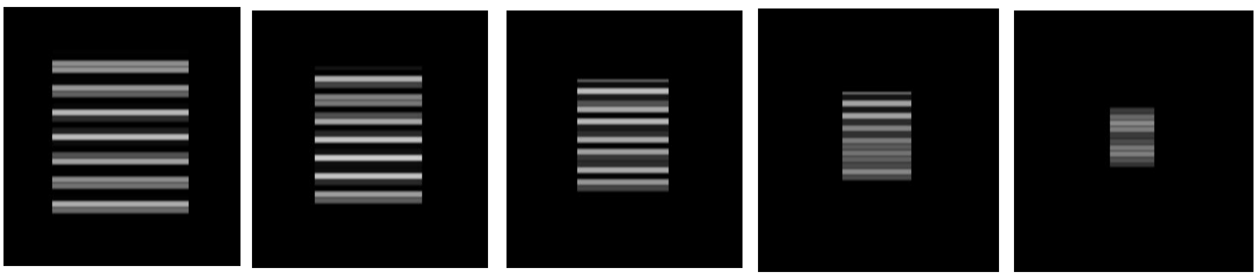

Figure 1. Resolution bar pattern displayed at five distances. Seven distinct bars are discernable at the nearest distances on the left and are undiscernible at the greatest distances on the right.

Variance in Current Measurements

The primary challenge with the current methods of measuring system resolution is that they produce highly variable results. The magnitude of this variation was measured in a 2007 study (Lloyd, 2007) of the repeatability of the lightpoint size test used by the FAA to certify Level D training devices. The results of that study, presented in Figure 2, reveal a standard deviation of the distribution at 12.0 percent of the mean and a ratio of the 5^{th} to the 95^{th} percentile measurements of 1.40. An unfortunate consequence of this wide spread in the test scores is that the most demanding evaluator may require nearly twice as many pixels, projectors, and IG channels ($1.4^2 = 1.96$) as the least demanding evaluator.

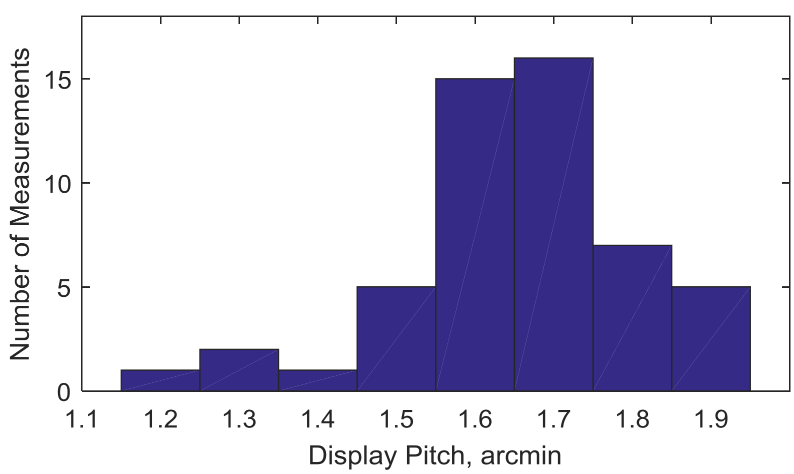

Figure 2. Histogram of the subjective resolution measurements from 13 experienced technicians using the FAA lightpoint size test. The standard deviation of the distribution is 12% of the mean.

The high variance in the current subjective measures of resolution was confirmed in a 2015 study (Lloyd, 2015) in which the variation in resolution measurements made by nine experienced Display Systems Engineers (DSEs) was evaluated. In that study the DSEs used horizontal and vertical grating patterns and adjusted the observation distance so that the patterns were just discernable. The standard deviation of the 18 measurements made by each of the nine DSEs (N = 162) was 12.1 percent of the measured resolution. The resolution measurement procedure exercised by the DSEs required an average of two minutes per measurement once the display/IG system was turned on and the test patterns were loaded.

The high variance of the current resolution measurement procedure stands out in comparison with the variance of the procedures used regularly to measure other dimensions of training display systems. Examples include:

- Latency and frame rate: Instrument std. dev. < 0.01% of the measured level
- Geometry and FOV: Theodolite error < 0.03% of the FOV
- Luminance and contrast: Std. dev. < 1 % of the measured level
- Chromaticity: Meter std. dev. < 0.5% of the range

In comparison, the inherent variation in the current resolution measurement procedure is on the order of 10 to 1000 times higher than the variation in these other objective measures of display system performance.

Opportunity for Improvement

System resolution is arguably the most important determinant of display system performance for military training applications since it has a strong effect on the distance at which students can observe and fight. The system resolution requirement is also one of the strongest determinants of the cost of the training system because the number of image generator channels, projectors, blend plate assemblies, cables, and equipment racks increases with the square of the resolution requirement. For example, increasing the display system resolution requirement from 20 to 30 cycles/degree increases the equipment cost by a factor of $(30/20)^2 = 2.25$.

Curiously, an objective camera-based measure of display resolution was used by the Air Force for many years from the mid-60s to the mid-80s. A review of the history of this capability can be found in the 2013 paper by Lloyd & Basinger. With the "Observer Camera" method developed by the AFRL, a specialized test pattern and calibrated camera system were used to measure the MTF of the display. While this method produced objective and precise measurements of display resolution, it was expensive, confined to the laboratory, and required extensive training to perform. The observer camera method fell out of use in the mid-80s when contracting practices changed and the Air Force no longer directly acquired display systems but relied on prime contractors to acquire and integrate the display systems into training devices.

Today, we are afforded the opportunity to re-introduce an objective measure of system resolution for simulation training devices. The development of capable digital cameras and portable computers, simple graphical user interfaces, image processing software, and IG-based test patterns have reduced the cost and complexity of making objective resolution measurements to inconsequential levels.

Variance Reduction Strategies

The precision of the current resolution measurement method is limited for a variety of reasons. Feedback obtained from the participants in our previous studies reveals that differences in the interpretation of "discernable modulation" is a primary source of variance. Some evaluators require that the bars or points of light observed in the test pattern appear of equal size and spacing while others consider any variation (including Moiré patterns) to be acceptable. A second source of variance arises from the fact that the modulation of the grating pattern can change significantly with small movements of the pattern relative to the pixel structure of the display. To combat this problem, DSEs will often slowly adjust the "phase" of the pattern so that they can observe the average modulation at a particular pattern distance. A third source of variation with the current procedure is apparently due to differences in the visual acuity of the evaluators. In our studies we observed that some evaluators would move up closer to the display screen when measuring resolution or would look at the test pattern through a magnifier. These evaluators explained they did not want the measurements to depend on their own visual acuity.

With the proposed method of measuring resolution these sources of variation are eliminated. The use of a test pattern with many bars allows the software to take the average across many cycles of the signal that the display system is attempting to reproduce. By using a radial grating pattern, very few of the lines in the pattern are parallel to the columns or rows of pixels on the display system. Thus, a single pattern naturally presents all possible phases of the lines relative to the pixel structure. With a radial grating pattern, the spacing between the lines decreases with distance from the edge of the patterns, thus, the pattern essentially presents many distances simultaneously. Also, by using a mathematically-defined linear spatial filtering approach, there is no ambiguity in the definition of discernable modulation, and the criterion for acceptable modulation does not vary with evaluator or depend on their visual acuity.

The strategy of using test patterns that simultaneously present many combinations of grating size and orientation has been around for decades. One common pattern that has been demonstrated recently by Streid (2014) for evaluating training display systems is the 1951 USAF resolution chart as shown in Figure 3. The primary benefits of simultaneously presenting many grating patterns are that resolution can be measured more quickly and the evaluator does not require real time control of test pattern distance. While the use of the AF chart is a step in the right direction, it does not take us as far as we can go with the strategy of simultaneous measurement. For example, the AF chart uses discrete levels of pattern spacing (distance), two orientations, and does not vary the phase of the pattern relative to the display.

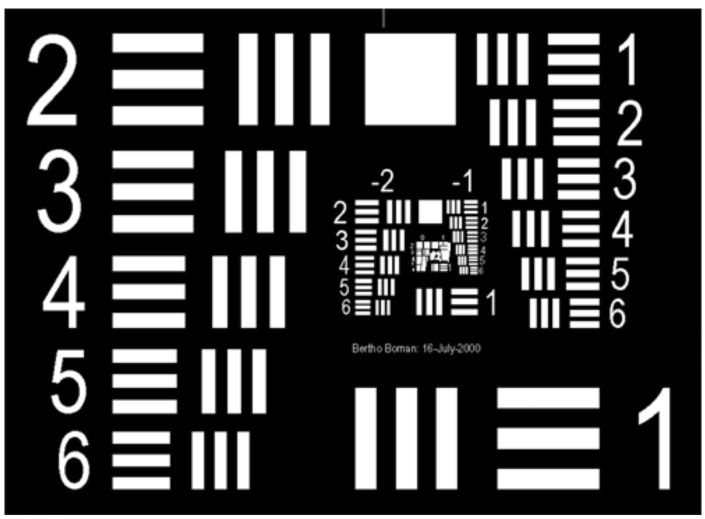

Figure 3. 1951 USAF resolution test chart.

With both the AF test chart and the grating patterns used with the current subjective methods, the bars are oriented normal to the line of sight of the observer and thus appear parallel. An alternative method of simultaneously presenting many distances would be to use a single long grating pattern and orient it such that the left end of the grating is near the observer and the right end is far away as illustrated in Figure 4. Figure 5 provides a photograph showing how this pattern appears when presented on a display/IG system that used very good antialiasing of the lines in the pattern. And Figure 7 shows how the pattern would look with this strategy applied for all orientations of grating patterns on the display.

In Figure 6, the seven bar grating pattern is rendered using poor antialiasing which produces noticeable spatial sampling artifacts. In a previous paper (Lloyd, 2013) we demonstrated how this pattern's ability to reveal these artifacts can be used to precisely quantify the magnitude of the spatial sampling artifacts that may be introduced by system components and processes such as line and edge rendering methods, a lack of antialiasing, image warping, image re-sampling, digital zoom, and projector-centric processes such as digital keystone correction.

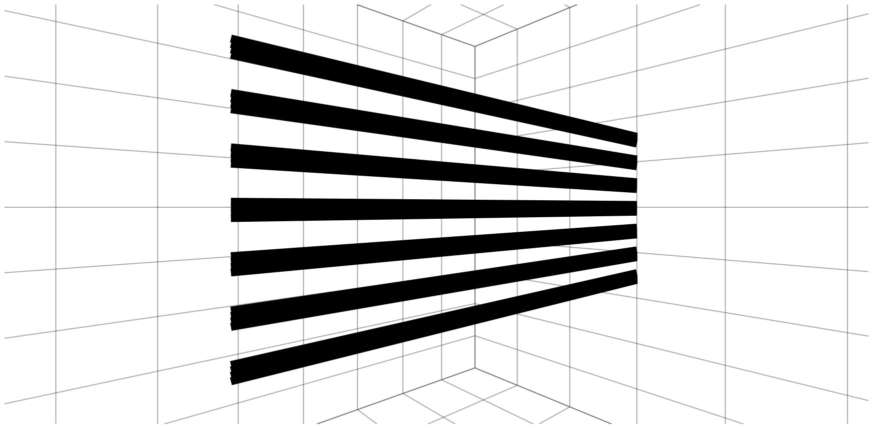

Figure 4. Example of a long seven bar grating pattern oriented such that it is closer to the observer on the left and farther away on the right.

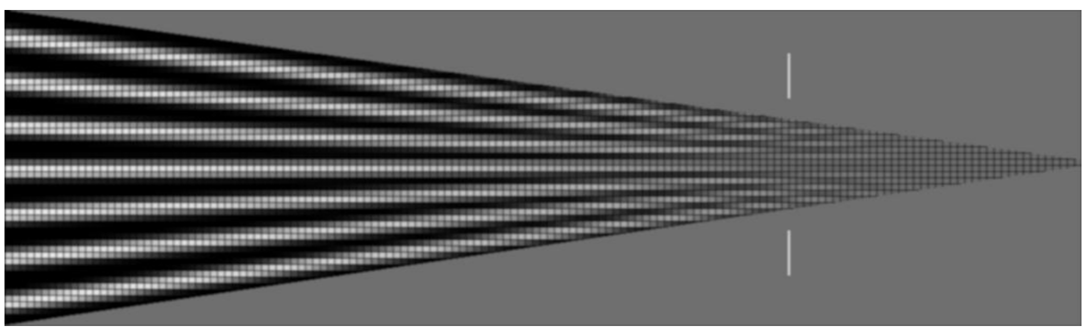

Figure 5. Seven bar pattern oriented to be near on left and far on right. Pattern is functionally equivalent to 150 separate grating patterns that are each one pixel wide and presented at a different distance. Pattern was rendered using very good antialiasing.

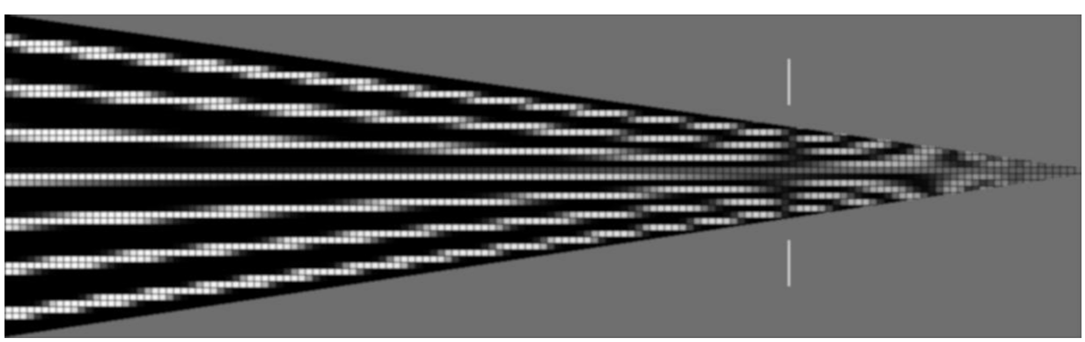

Figure 6. Seven bar pattern oriented to be near on left and far on right, rendered with minimal anti-aliasing producing substantial spatial sampling artifacts.

PROPOSED METRIC, TEST PATTERN AND PROCEDURE

This section describes the proposed MTP which is published for consideration by acquisition professionals and suppliers in the simulation training community.

Goals

The goal of this metric is to quantify static resolution and the magnitude of spatial sampling artifacts produced by a display and image generation system. These two dimensions of display system performance are measured simultaneously using a single test pattern, image capture, and image analysis in order to characterize the specific design trade that has been made between resolution and artifact magnitude. These metrics require the use of IG-based test patterns so that the metrics account for the effects of all components in the imaging chain including polygon rendering and overlay methods, anti-aliasing, image re-sampling (i.e., geometry correction), as well as the projector, lens, screen, mirror, and the effects of inter-reflections that can reduce system contrast.

Scope

This MTP is designed for assessing single or multi-channel display and image generation systems that provide a visual scene surrounding the observer. The metric is suitable for use in the body of each display channel where resolution changes little over the spatial extent of a single test pattern. The metric is not recommended for use in the blend regions between channels where resolution can be highly variable and anisotropic due to the misalignment of one channel relative to an overlapping neighbor channel.

It is assumed that measurement procedures requiring frequent test pattern changes are not practical for display measurement events using customer-supplied measurement equipment because the measurement system may not have control of the image generator-based test patterns. Thus, this MTP was designed to accommodate the use of many test patterns simultaneously displayed across the total field of view (TFOV) of a display system in order to minimize the number of test pattern changes that would be required to characterize a system.

Test Pattern Definition

The test pattern shall be created using the image generator and must be subjected to all of the image processing steps that are applied to the images used for training. The test pattern shall be created using 131 white polygons on a black background arranged in a regular radial grating pattern as shown in Figure 7. The angular width of the black spaces between polygons shall be four times the width of the white triangular polygons for a duty cycle of 20%. The pattern shall be movable such that it can be positioned in any part of the TFOV of the display system. A means must be provided to allow the user to set the modeled distance of the pattern such that the height of the radial grating spans 300 +/- 15 display system pixels.

The pattern must include four small black squares surrounded by four larger white squares in the corners of the pattern as shown in Figure 7. These black-white square features serve as alignment marks that are used by the pattern analysis software to locate features within the pattern. The height of the white squares is 1/12th of the height of the radial pattern and the black squares are 1/36th of the height of the radial pattern.

The pattern must include a 2x2 checkerboard camera focus pattern at the center of the radial pattern. The four blocks that make up the 2x2 checkerboard span 1/10th of the radial grating pattern height and each check is 1/20th of the pattern height.

Positioned to the sides of the radial pattern shall be ten larger squares that are used to determine if the electro-optical response (i.e., gamma) of the display system is accurate enough that the system resolution and sampling artifact measurements are valid. The size of these squares is 1/5th of the height of the radial grating pattern. The commanded levels of the left five squares shall be (from top to bottom): 0/9, 4/9, 8/9, 6/9, and 2/9 of the peak white luminance of the display system. The commanded levels of the right five squares shall be (from top to bottom): 3/9, 7/9, 9/9, 5/9, and 1/9 of the peak white luminance of the display system.

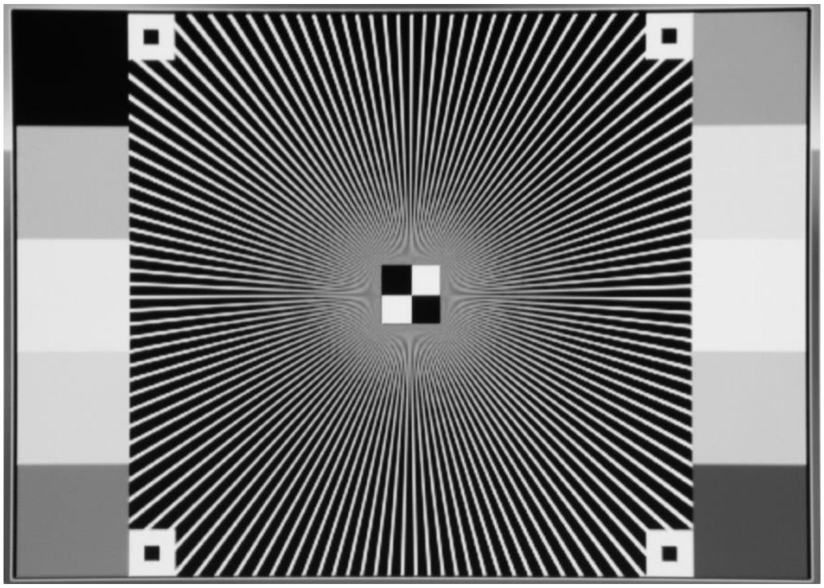

Figure 7: Test pattern used for the System Resolution and Sampling Artifact measurements.

The test pattern shall be created on the same image generator that is used to create the images used during training. The test pattern shall be subjected to all of the same image processing and optical stages used in training including polygon generation, antialiasing, texture mapping, image remapping (warping), color correction, gamma correction, uniformity correction, channel blending, tone mapping, motion blur reduction, image transmission, stereoscopic display (including eyewear), and any other process that has the potential of changing the display system resolution or the magnitude of sampling artifacts present in the image during training. The test pattern(s) may be displayed against a black background. Multiple test patterns may be displayed on the system simultaneously to facilitate the rapid measurement of multiple portions of the FOV without requiring frequent test pattern changes.

Metric Description and Procedure

Display system resolution and sampling artifact magnitude are measured by displaying the test pattern on the display system under test (DSUT) and photographing it with a calibrated digital camera. The camera image is analyzed using software which computes the resolution and sampling artifact metrics, generates a standardized test report, and saves the summary data for the computation of display system metrics.

The steps involved in the computation of system resolution include:

- Find the image registration marks (small black squares inside white squares) at the corners of the radial pattern. These marks are used to reliably locate the other features within the image of the test pattern.
- Measure the grayscale response of the system using the five large squares along each side of the pattern. This measurement is used to determine if the grayscale linearity of the display system is within bounds so that the user can be warned if it is not.
- Compute a set of circular luminance scans at different diameters from the center of the radial pattern. Each scan represents the modulation present across a range of pattern orientations. The radius of the circle is proportional to the inverse of the spatial frequency of the pattern (in cycles/display pixel).
- Compute the Fourier transform of each circular luminance scan, scale the resulting transform, and compute the magnitude of the fundamental frequency in each scan.
- Plot modulation of the fundamental as a function of spatial frequency over the range of frequencies represented in the pattern (see Figure 8).
- Determine the limiting resolution of the system by finding the intersection of the measured modulation transfer function and the contrast threshold function indicating the contrast required as a function of spatial frequency.

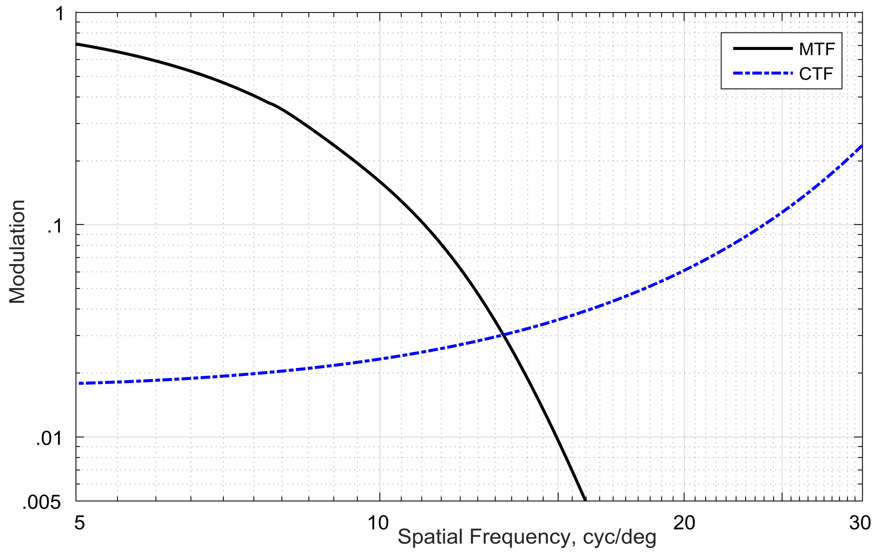

Figure 8. Example of the modulation transfer function (MTF) of a display system and contrast threshold function (CTF) of the standard observer. The limiting resolution of this display system is defined as the intersection of these curves and measures 13.2 cyc/deg (4.54 arcmin/OLP).

Measurement System Requirements

The radial grating pattern(s) shall be measured using a digital camera that is mounted on a pan-tilt unit that is positioned at the eyepoint. The native resolution of the camera shall be high enough and the camera lens zoom shall be set such that at least 6 camera pixels are used to measure each display pixel when the display pixel pitch is greater than 1.0 arcmin. When the display pixel pitch is less than 1 arcmin, the resolution and optical zoom of the camera shall produce a camera sampling rate that is no less than 6 samples per arcmin. The camera shall employ an optical low pass filter that eliminates the possibility of creating Moiré patterns due to the interaction between periodic test patterns and the spatial sampling mosaic of the camera. The luminance modulation transfer factor of the camera lens shall be no less than 0.80 at the resolution limit (mod = 10%) of the display system under test (DSUT). The measurement system shall compensate for the luminance MTF of the camera system for all combinations of zoom and aperture settings that are used for the measurements.

The measurement system shall be capable of moving at least 30 deg, capturing an image containing the radial grating pattern, processing the image, computing the metrics, and producing a text file with the measured values within 10 seconds. The system shall be capable of measuring resolution anywhere within the sphere except for a cone that extends below -60 degrees of elevation. The standard deviation of repeated measurements of resolution for a single test pattern shall be less than 1.5% of the measured value. The standard deviation of repeated measurements of sampling artifact magnitude for a single test pattern shall be less than 2.0% of the measured value.

PERFORMANCE OF PROPOSED METHOD

The primary advantage of the proposed metric is that it greatly reduces the variance in resolution measurements. The first evaluation of the method is reported in our 2013 study (Lloyd, 2013) which produced a standard deviation of repeated measurements of 1.0 percent of the measured resolution using a Canon G-9 camera to measure the resolution of a Sony liquid crystal on silicon (LCoS) projector. In a follow on study (Lloyd, 2014) the method was used to measure the relative effects of several display design parameters including projection screen type, antialiasing setting, lens mis-focus and color mis-convergence. For this study measurements were made using a Canon EOS T5i camera and the standard deviation of repeated measurements was < 1.0 %. The most recent evaluation of the precision of the proposed method was conducted in a dome display system employing four BARCO F-35 digital light processor (DLP) projectors. Results of this testing (Lloyd, 2015) produced a standard deviation of repeated measurements of 0.8% of the measured resolution. During this same field test the correlation between the proposed method and the current methods used by the nine DSEs who participated in the evaluation was highly reliable ($R^2 = 0.79$, 17 df).

Two years ago we constructed a simple pan/tilt unit (PTU) mockup (Lloyd, 2015; Lloyd, 2016) for the purpose of demonstrating the automated measurement of resolution using multiple test patterns displayed simultaneously across a large FOV display system. With this mockup resolution measurements were made at a rate of seven per minute which is 14 times faster than can be accomplished using the current subjective methods.

SUMMARY

The proposed metric has a solid theoretical foundation with a 50+ year history of use in other industries including film and digital photography, remote sensing, and military electro-optical systems design. From the mid-60s to the mid-80s camera-based measurements of MTF were required by the Air Force in support of the acquisition of displays for simulation trainers. It appears the method fell out of use by display system integrators due to the high cost and lack of portability of the equipment and the extensive training required to perform the measurements. In recent years these barriers to the adoption of an objective measure of resolution have been eliminated. The camera and portable computer required to make the measurements cost less than a few thousand dollars. The test pattern is currently available at no cost as an OpenFlight model. The software required to analyze camera images of the test pattern can be standardized and distributed to all stakeholders in the community so that everyone computes the metrics in exactly the same way.

From the point of view of the person conducting display system measurements in the field, the procedure for measuring system resolution could be as simple as follows:

1. Position the camera at the eyepoint
2. Display the standard resolution pattern at one or more locations across the display
3. Capture image(s) of the pattern
4. Load the image(s) to a laptop computer for metric computation and reporting

With a standardized metric definition, test pattern, and measurement procedure, the complexity of preparing requirements for display systems would be simplified because the display systems engineer can cite the MTP and would not need to replicate this information in their requirements document. Similarly, the development of a test plan would be simplified because the engineer can cite the MTP for the details of the metric, test pattern, and procedure.

Expected benefits

The primary benefits expected from the adoption of the proposed resolution MTP include:

- Measurement precision is improved by a factor of 12 relative to the current methods
- The speed of measurement can be increased by a factor of 14
- The complexity of preparing requirements and test plans is reduced because a standard method can be cited
- The technical expertise required of the persons who prepare requirements and test plans and conduct the tests is substantially reduced.
- The use of a standardized, precise, and fast method of measuring resolution enables more comprehensive measurements that can be compared across programs and over time.

Limitations and Next Steps

To date we have completed multiple laboratory tests of the proposed MTP but have conducted limited field testing. One concern noted during an early demonstration of the method was that the test pattern is larger than the patterns typically used with the current procedure. Thus, the proposed test pattern cannot be used as close to the edges of a display channel as the current pattern allows. Similarly, the test pattern does not work well for measuring resolution in blend regions where resolution can be highly variable and anisotropic due to the misalignment of one channel relative to an overlapping neighbor channel. Thus, we do not recommend using the pattern for blend zone resolution but encourage the use of a “geometry co-alignment” metric which more directly measures this dimension of system performance.

With the current pattern definition one can simultaneously display approximately 16 to 20 patterns spread across a typical display channel. Over the coming year we will evaluate the use of a smaller version of the radial grating pattern and alternative methods of measuring resolution in the blend regions. And over the coming year we expect to demonstrate the method at other laboratories and training sites and to collect feedback from stakeholders so that the MTP may be improved to better meet the needs of the simulation training community.

REFERENCES

Barton, P G. J. (2000). Contrast sensitivity of the human eye and its effects on image quality. SPIE Press.

Beaton, R. J. (1984). A human-performance based evaluation of quality metrics for hard-copy and soft-copy digital imaging systems. Dissertation, Virginia Polytechnic Institute and State University, Blacksburg.

Boreman, G. D. (2001). Modulation Transfer Function in Optical and Electro-Optical Systems. Tutorial Texts in Optical Engineering Volume TT52, Society of Photo-Optical Instrumentation Engineers (SPIE).

FAA (1995) Advisory Circular, 120-40C Draft, Airplane Simulator Qualification.

Fiete, R. D. (2010). Modeling the imaging chain of digital cameras. Tutorial Texts in Optical Engineering Volume TT92, Society of Photo-Optical Instrumentation Engineers (SPIE).

Holst, G. C. (2000). Electro-optical imaging system performance. SPIE Press, Bellingham, WA

ICAO (2003). Manual of Criteria for the Qualification of FSTD, Document 9625, second edition.

JAR (2003). STD 1-A, Amend 3, 1 July 2003.

Lloyd, C. J. (2007). Rendering high quality lightpoints on fixed matrix displays. *Proceedings of the IMAGE Society Annual Conference*, The IMAGE Society, Phoenix, AZ.

Lloyd, C. J. (2011). Towards a decision support system for simulation training display requirements. *Proceedings of the Interservice/Industry Training, Simulation, and Education Conference,* Orlando, FL.

Lloyd, C. J., Joralmon, D., Amann, R, Tai, C., Williams, L., and Pierce, B. (2011). Relative effects of five display design variables on aircraft identification range in daylight. *Proceedings of the IMAGE Society Annual Conference,* The IMAGE Society, Scottsdale, AZ.

Lloyd, C. J., Williams, L., and Pierce, B. (2011). A model of the relative effects of key task and display design parameters on training task performance. *Proceedings of the IMAGE Society Annual Conference,* The IMAGE Society, Scottsdale, AZ.

Lloyd, C. J. (2012). Effects of spatial resolution and antialiasing on (3D) stereoacuity and comfort. *Proceedings of the 2012 AIAA Modeling and Simulation Technologies Conference,* Minneapolis, MN.

Lloyd, C. J. (2013). Towards a Metric of Antialiasing Sufficiency for Stereoscopic Displays. *Proceedings of the Stereoscopic Displays and Applications XXIV Conference,* SPIE, Vol 8648.

Lloyd, C. J. and Basinger, J. D. (2013). Towards an objective and affordable metric of display system resolution. *Proceedings of the IMAGE Society Annual Conference*, The IMAGE Society, Phoenix, AZ.

Lloyd, C. J. (2014). Determinants of system resolution for modern simulation training display systems. *Proceedings of the IMAGE Society Annual Conference,* The IMAGE Society, Phoenix, AZ.

Lloyd, C. J. (2015). Alpha test of resolution measurements for the display measurement toolkit (DMT). Technical Report DMT-Alpha-001. Visual Performance LLC, Ellisville Missouri.

Lloyd, C. J. (2016). Demonstration of automated resolution measurements for the display measurement toolkit (DMT). Technical Report DMT-Alpha-003. Visual Performance LLC, Ellisville Missouri.

Snyder, H. L. (1985). The visual system: Capabilities and limitations. In L. E., Tannas (Ed.) Flat-panel displays and CRTs, pp. 54-69, New York: Van Nostrand Reinhold.

Snyder, H. L., Keesee, R., Beamon, W. S., & Aschenbach, J. R. (1974). Visual Search and Image Quality. Technical Report AMRL-TR-73_114. Dayton, OH: Air Force Aerosapce Medical Research Laboratory.

Streid (2014). Demonstration of the Boeing Constant Resolution Visual System (CRVS), Recorded at the Interservice/Industry Training, Simulation, and Education Conference. Posted on Youtube at https://www.youtube.com/watch?v=iUCtAnXDrKY

Task, H. L. (1979). An evaluation and comparison of several measures of image quality for television displays. Wright-Patterson AFB, Report AMRL-TR-79-7.

Vollmerhausen, R. H., Reago, D. A., & Driggers, R. G. (2010). Analysis and evaluation of sampled imaging systems. Bellingham, WA: SPIE Press.