TOWARDS AN OBJECTIVE AND AFFORDABLE METRIC OF DISPLAY SYSTEM RESOLUTION

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ABSTRACT

Camera-based measures of display system resolution were developed many decades ago and were used in the military simulation training industry as early as the mid 1960s. Metrics based on the modulation transfer function (MTF), such as the modulation transfer function area (MTFA) and square root integral (SQRI), received much research attention and were shown to correlate well with performance on a range of tasks. However, in the mid 1980s the camera-based metrics fell out of use and were replaced by subjective assessments using grating patterns. This paper summarizes attributes of the early measures that contributed to their demise including: cost, complexity, difficulty of measuring from the eyepoint, and lack of consideration of sampling and artifacts. Subsequently, a description is provided of a practical and affordable camera-based metric for display system resolution that also accounts for sampling artifacts and the effects of antialiasing. The use of the proposed metric to measure display system resolution from the eyepoint is described and illustrated.

GOALS AND AUDIENCE

This paper addresses the need for an improved objective metric for imaging system performance that correlates with visual performance, while overcoming the limitations of prior camera-based MTF metrics. The paper is written from the point of view of the commercial or military acquisition professional who must establish performance-based requirements for training devices, or system integrators who need to characterize the performance of their product offerings. This work follows from the research and development agenda for the Immersive Display Evaluation and Assessment Study (IDEAS) that began in 2010 under the sponsorship of the Air Force Research Laboratory (AFRL). The goals of this program include the development of more effective display system metrics that are defensible on the basis of training task performance. Many concepts presented in this paper were described in two papers (Lloyd 2011, Lloyd, Williams et. al., 2011) that model and validate the effects of key display system design variables on aircraft identification range. In these earlier papers, the limiting resolution of a training display system was based on key design parameters including pixel pitch and motion-induced blurring, however, those papers did not address the *measurement* of resolution. The present paper discusses the goals for, and design of, a measurement procedure that addresses display system resolution in a more comprehensive way than do previous metrics.

CURRENT MEASUREMENT METHOD

For more than two decades the simulation training industry has relied primarily on the use of subjective measures of display system resolution. Based largely on the FAA/JAA defined “lightpoint size” and “vernier resolution” tests, display system acceptance is typically accomplished by displaying the requisite patterns and having the evaluator look at the pattern from the eyepoint position and determine if modulation is “discernible” (FAA, 1995; JAA, 2003). Due to the lack of definition of discernible modulation, and the unavoidable differences across observers, the outcome of this test can be highly variable. The results of a repeatability study revealed a +/- 20% difference across observers performing the JAA lightpoint size test (Lloyd, 2007). Figure 1 shows the spread of pixel pitches that were required to pass this test. The Standard Error of the Mean (SEM) for these estimates was 0.12. These data indicate that the 95th percentile test outcome required a display system with twice as many pixels (and thus projectors and image generator channels) as did the 5th percentile test outcome.

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In sharp contrast with this highly variable subjective measure of resolution, we typically measure other key display design variables with far greater precision. For example, the measurement of the field of view of a display system is regularly performed using a theodolite that is repeatable to better than 0.001% of the typical field of view requirement. Temporal measures such as update rate and delay are measurable to better than one percent of the requirement. Display system luminance and contrast are measured with commonly available meters that are repeatable to within a few percent of the requirement.

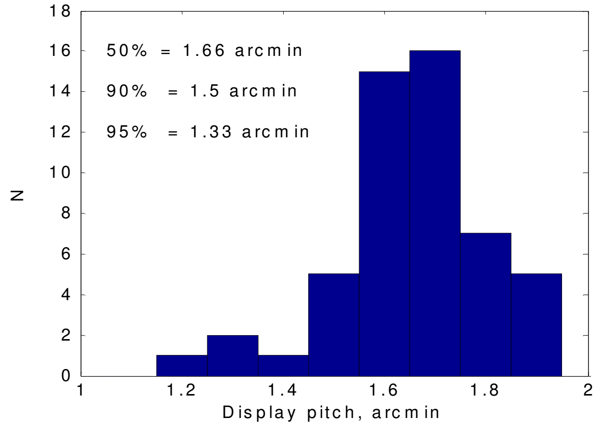

Figure 1. Histogram of "barely acceptable" pitch estimates required to pass the JAA lightpoint size test. Four estimates are shown for each of 13 observers for a total of 52 estimates and a standard deviation of 0.2 arcmin. The majority of the variance in these data (75%) is due to the differences between observers.

Given that display system resolution is one of the strongest drivers of both the performance and cost of a training display system, it is curious that few in the simulation training industry currently use an objective measure of display system resolution. In the remainder of this paper, we review the history of objective resolution measurements as well as the camera-based technique that was once used by the US Air Force for the specification and acceptance testing of display systems. Taking the lessons learned from this historical review, we go on to describe and illustrate the use of an improved objective measure of display system resolution that we expect will substantially improve the precision with which we can measure this most important design parameter.

HISTORY OF OBJECTIVE METRICS

The development and evaluation of objective image quality metrics began more than 50 years ago. In 1974, Snyder and his colleagues reported reviewing over 300 laboratory and analytical studies designed to assess the relationship between variations in television display image parameters and observer performance that had been published since 1962. One of the best overviews of the image quality research for photographic and electronic display systems can be found in Biberman (1973). Side-by-side comparisons of the most promising objective metrics developed over the following decade were conducted by Task (1979) and Beaton (1984). The most recent summaries of this research can be found in Decker et. al., (1987) and Snyder (1985 and 1988).

Of all the objective measures of image quality that were considered over this 25 year period, the modulation transfer function area (MTFA) metric emerged as the most thoroughly tested metric that was shown to correlate strongly with observer performance for a wide range of tasks. The MTFA metric was successful enough at predicting observer performance that it was selected for use as an acceptance standard for video display terminals by the American National Standards Institute (ANSI) and the Human Factors Society (HFS, 1988).

The MTFA metric was first introduced by Charman and Olin in 1965 for use in evaluating photographic images. This metric provides a concise way to account for the overall capability of an imaging system as well as the visual capability of the observer. The MTFA calculation, illustrated in Figure 2, is defined as the area bounded by the MTF of the imaging system and the contrast threshold function (CTF) of the observer. The limiting resolution of the imaging system occurs where the MTF and the CTF curves intersect. The MTFA metric concept was extended by Lloyd and Beaton (1990) who developed the JNDA metric that non-linearly scales the area between the CTF and the MTF using the number of just-noticeable-differences (JNDs) in contrast, following the earlier work of Carlson & Cohen (1980). A similar extension of the MTFA style metric was developed and thoroughly tested by Barten (2000) who summarizes much of his extensive validation work in his recent book.

SCANNING PHOTOMETER METHOD

The MTFA measurements made by many of the researchers cited above, as well as researchers in other laboratories (Verona, Task, et. al 1979), were typically performed using a scanning photometer. The most common instrument of the time was the Gamma Scientific scanning telemicro-photometer fitted with a 10 micron wide slit that was mounted on a three-axis mechanical stage that allowed precise positioning of the instrument relative to the display device under test. This instrument had a working distance of less than a few inches and a depth of focus of less than 1 mm. Since a luminance scan required a minute or more to complete, many laboratories conducted the measurements on floating optical tables that isolated the equipment from vibrations. The photometer used a photomultiplier tube that required a half hour or more to warm up and could be damaged if exposed directly to a bright light source. This equipment was typically operated under the control of a mini-computer such as an HP 9826 desktop computer or a DEC PDP-11-55 minicomputer which could also perform data reduction and summary calculations. The characterization of a display device often required additional equipment such as a strip chart recorder, capable video pattern generator, high bandwidth oscilloscope, and a NIST-tracable luminance standard. Given the high cost and complexity of the equipment, short working distance, and susceptibility to vibrations, display system measurements of this era were confined to the laboratory.

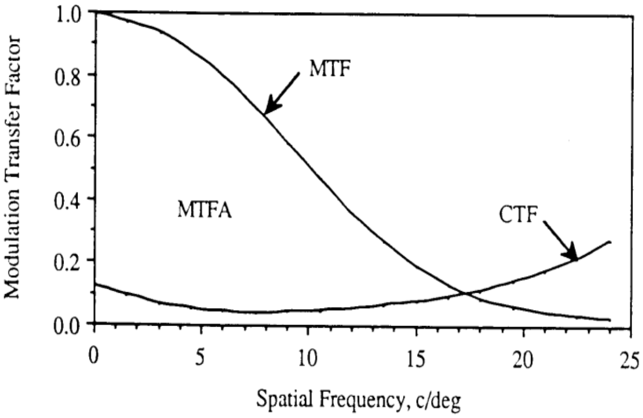

Figure 2. Illustration of the computation of the Modulation Transfer Function Area metric.

USAF OBSERVER CAMERA TECHNIQUE

During the same time period that the broader display community was researching and developing image quality metrics, the Aerospace Medical Research Laboratory (now Air Force Research Laboratories, after many reorganizations and consolidations) developed and employed a camera-based measurement system that objectively measured the MTF of a television system. During the 1960s, the application of closed circuit television (CCTV) to visual simulation was in its infancy. The Aerospace Medical Research Laboratory's Simulation Techniques Branch was developing enhancements to CCTV to improve visual simulation. As a part of this effort, the observer camera technique was developed to measure modulation transfer function (MTF) objectively (Harshbarger, 1964, 1965). Prior to this time, the specification and acceptance testing of visual simulation systems utilized subjective observation of resolution which was not well received in the military contracting community. The observer camera technique permitted MTF to be objectively specified and measured as the CCTV technology improved and applied to visual simulation acquisition programs.

The observer camera technique measures the amplitude of an analog video signal waveform to obtain MTF. This waveform is analyzed on an oscilloscope and is a portion of a single television scan line from:

- A television camera viewing a resolution pattern
- The analog output of various video equipment (such as video amplifiers), or
- An observer camera viewing a small portion of the image generated by another television system viewing a resolution pattern.

A primary objective of the observer camera technique was to eliminate the human observer for more reliable and repeatable equipment testing.

For the MTF measurements to be accurate, the resolution pattern must have 100% contrast ratio or be measured to modify oscilloscope measurements. The television system under evaluation must be stable mechanically and electrically while viewing the resolution pattern. If using an observer camera, the camera must:

- View a small portion of the image under evaluation to ensure the MTF of the observer camera will be 100% at the specified/test MTF,
- Be able to sense a higher contrast ratio than the image under evaluation, and
- Be mechanical and electrically stable.

The equipment required for the observer camera technique included:

- A physical test pattern,
- An image generator television camera
- A high quality television camera with high quality long lens to be the observer camera,

- A sync signal generator and distribution equipment,
- An oscilloscope with two variable “delay trigger” generators with “intensifying pulse”, and
- A film camera mounted on the oscilloscope to record results.

Like the scanning photometer approach described above, the observer camera technique was complex, expensive, and typically confined to the laboratory.

In the 1960s through the mid-1980s, the Air Force contracted for most visual simulation systems independently of the aircraft simulator system. Both systems were separately specified, contracted, tested and accepted before integration. After the development of the observer camera technique, acquisition contracts for visual simulation systems specified MTF and specified observer camera measurement of MTF for acceptance testing. The emphasis was on objective measurement of a subjective attribute of visual simulation. Air Force contracting officers insisted on objective specifications and acceptance test procedures whenever possible.

Decline of the Observer Camera Method

In the mid-1980s, Air Force simulator contracting evolved to specifying a total training system. The practice of specifying MTF and the observer camera test method were dropped as visual simulation subsystem performance was no longer being specified in the request for proposals (RFP). The offerors, in response to the RFP, were required to propose visual simulation subsystem performance specification and test methods. These proposed specification and test methods are evaluated by the government and incorporated into the awarded contract. Source selection decisions were no longer based on a-priori measurements of display system resolution and the supplier was free to select the method of measuring this attribute of a display system. The use of objective measures of resolution quickly declined and subjective measures again dominated for Air Force programs.

NAVY METHOD

For the past several decades the US Navy has employed a different approach for measuring display system resolution than has the Air Force. The Navy method is essentially a hybrid approach incorporating both subjective and objective measures. With this method a multi-bar grating pattern is displayed on the system that can be positioned at different locations within the field of view. The resolution measurement is conducted using a procedure similar to the psychophysical method of adjustment. With this procedure the test pattern is moved away from the observer until the modulation is just invisible. The pattern is then moved towards the observer until it becomes just visible again. This procedure is repeated several times until the observers are satisfied that the modulation in the pattern is at threshold. If the stakeholders conducting the test cannot agree on the test outcome, then the modulation of the pattern can measured using a sensitive photometer with a small aperture (i.e., the PR-1980). In practice, however, the photometer measurement of the test pattern is rarely used as agreement is typically obtained using the subjective test method.

EFFECTIVE METRIC ATTRIBUTES

At the most fundamental level, our present goals are the same as those of the pioneers in this arena: Identify and employ a metric of display system resolution that correlates strongly with task performance and exhibits much less variance than the subjective measures. We applaud the pioneers who did the hard work of identifying what should be measured and validating the effects on performance… back when making the measurements and computations was no easy task. Today the availability of modern digital cameras, powerful portable computers, and image generator-based test patterns makes the job of measuring and computing the metric far easier. These new technologies afford us the luxury of significantly expanding our goals for the metric design. Thus, the metric described in this paper was designed to:

- Correlate strongly with task performance
- Exhibit significantly less variance than current subjective measures
- Have a clearly defined method of measurement
- Be measurable from the eyepoint(s) in completed training devices as well as in the laboratory
- Account for all sources of degradation in the imaging chain including spatial sampling and artifacts
- Account for the visual capability of the users
- Use common, practical, and affordable equipment
- Require no more than a few minutes to measure and compute
- Not require fixtures or reconfiguration of the training device (e.g, removal of cockpit seats)
- Use movable test patterns to allow characterization of different portions of the field of view
- Accommodate any pixel sampling structure, color filter mosaic, or pixel orientation
- Allow measurement of blend regions with multiple overlapping images

- Simultaneously measure multiple conditions (i.e., all line orientations and a range of spatial frequencies)
- Enable computer control of the camera and image transfer to support automated testing

PROPOSED METRIC

With the proposed metric, the modulation of the display system is measured as a function of spatial frequency using an image generator based test pattern. The pattern is displayed on the training display in the desired location(s) and photographed using a modern consumer digital camera. The photograph is transferred to a portable computer for analysis and computation of the metric.

Test pattern and apparatus

The proposed test pattern was created using 149 white anti-aliased polygons regularly spaced in a radial pattern against a black background as shown in Figure 3. The duty cycle of the pattern was set to 20% for the white polygons. The radial portion of the test pattern spanned 300 pixels on the display system which produced a sampling rate of six samples per cycle (three times the Nyquist sampling limit) of the pattern at the top, bottom, left, and right edges of the pattern. The gamma assumption in the test pattern software was adjusted to produce a linear grayscale relationship accurate to within a few percent of the peak luminance. Luminance and grayscale linearity were measured using a Minolta LS-100 luminance meter and a display system linearity correction was applied. For the examples described here the test pattern was displayed using a Sony VPL HW30ES LCoS projector. This projector produced an image with 1920 x 1080 pixels spanning 40 x 23 inches on a wall 68 inches from the projector. At this distance and image size, the luminance of the image was 46 fL. Accounting for the neutral density filter in the camera, the effective image luminance was 5.8 fL.

All images in this report were captured using a Canon G-9 consumer color camera that was purchased circa 2008 for approximately $500. The image size control of the camera was set to produce images with 4000 x 3000 (12 MPix) pixels. Images were downloaded using the JPEG format to a PC for processing. The image compression control on the camera was set to "super fine" which produced image files that were 6.5 MB on average. The grayscale response of the camera (and compression) was measured and a correction equation was used to linearize the camera response. The camera exposure control was set to aperture priority mode and the aperture set to f = 8.0 which produced exposure times of 1/15 sec.

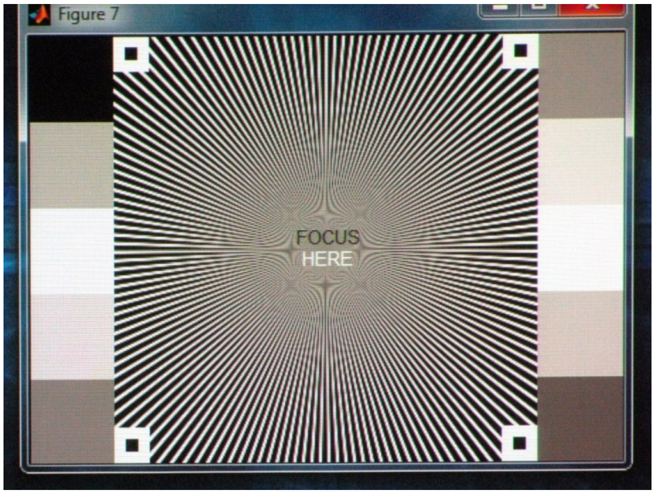

Figure 3. Photograph of the test pattern as presented on the display system to be measured.

The ND filter within the camera was engaged so the camera would average over several frames and the effective image luminance would be representative of typical simulation trainers. The smallest aperture setting for this camera was selected so that the diffraction limited blur function produced by the camera lens would assure the camera was fully antialiased. Image stabilization was turned off and the camera was focused with the autofocus function set to "center." The zoom setting of the camera was set such that the test pattern image filled the camera frame. With this setup approximately 2700 camera pixels spanned the radial test pattern, for a ratio of 9 camera pixels per display pixel. The camera was mounted on a tripod and a 2 sec delay was used to allow the camera/tripod to cease vibrating before each shot.

Metric Computation

This section provides the highlights of the computation of the metric, providing enough detail to allow the reader to understand the nature, complexity, and speed of the process. A goal of this paper is to demonstrate the practicality and utility of using a camera-based objective metric of display system resolution and to stimulate others to collaborate with us on the development and testing of such a metric. It is premature to publish a detailed recipe for this metric as we have not yet completed testing. We are currently developing multiple variants of the test pattern and metric and are comparing their relative performance. The details of our best candidate metric(s) will be provided in a future publication.

The steps involved in the computation of this metric 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 camera image.
- 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 linearity of the display system is within bounds and warn the user 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 all pattern orientations. The diameter of the circle is proportional to 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.

The computation of the metric was performed on a Windows PC running the MATLAB software and required a few seconds to complete. We are considering supplying a compiled version of our analysis software to parties interested in research collaboration so that they do not have to purchase the MATLAB software to work with us on the development and testing of the metric.

Camera Selection Considerations

Thus far our testing has indicated that consumer color cameras comparable to the Canon G9 should work well for measuring display system resolution as long as the appropriate settings are used and key dimensions of the camera response have been measured and calibrated. Prior to making the measurements reported here, the grayscale response of the camera was measured and the best linear combination of the image primaries was computed to maximize the correlation with luminance. When making MTF measurements one must account for the MTF of the camera and account for this in the calculation of the MTF of the display system. Figure 4 shows a small section of the image shown in Figure 3 and illustrates the small reduction in modulation introduced by the camera. For the measurements reported in this paper the MTF of the camera was approximately 0.8 at the sampling limit of the display system and was compensated for in the calculation of the MTF.

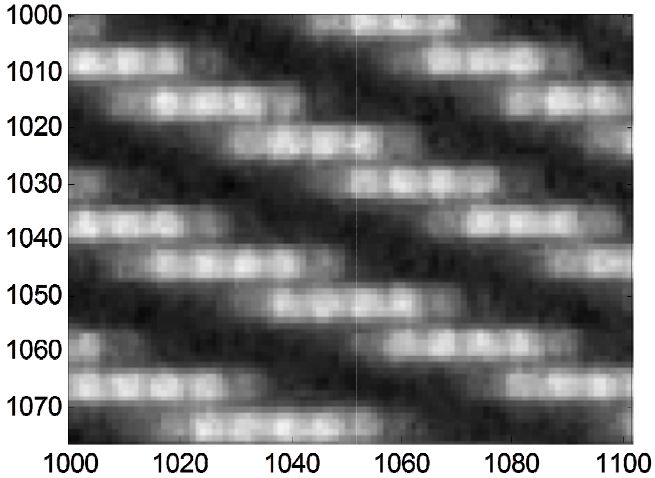

Figure 4. Small section of the image in Figure 3 containing 100 x 78 camera pixels. Image illustrates this camera is capable of transitioning from near minimum to near maximum luminance within approximately 4 camera pixels.

Measurement Results

The results of five repeated MTF measurements are shown in Figure 5. For each measurement, the position of the test pattern was changed relative to the pixel structure of the display; which produced much of the variance between the repeated measurements.

With the proposed metric the limiting resolution of the display system is computed by finding the crossover point between the MTF and CTF curves. For the example shown in Figure 5, the crossover point occurred at an average spatial frequency of 25.4 cycles per degree. The MTF measurement and computation was repeated five times at each of 14 settings for the antialiasing filter width for a total of 70 measurements. The results were converted to the more familiar units of arcmin / optical line pair and are plotted in Figure 6. These results indicate that the current method allows display system resolution to be measured with a standard deviation that is 1.0% of the mean. Comparing this with the 12% variation obtained with the most commonly used subjective measure; it is clear the proposed method offers a substantial reduction in the variability of display system resolution measurements.

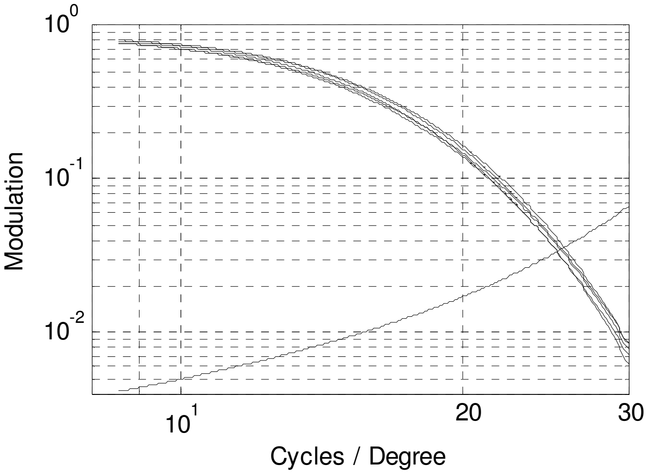

Figure 5. Five display system MTF measurements using the radial grating pattern shown in Figure 3 with the antialiasing filter width set to 1.3 pixels. The viewing distance was set to produce a pixel pitch of 1.0 arcmin and a theoretical sampling limit of 30 cyc/deg. The lower curve shows the Contrast Threshold Function (CTF) of the observer assuming a display system luminance of 6 fL.

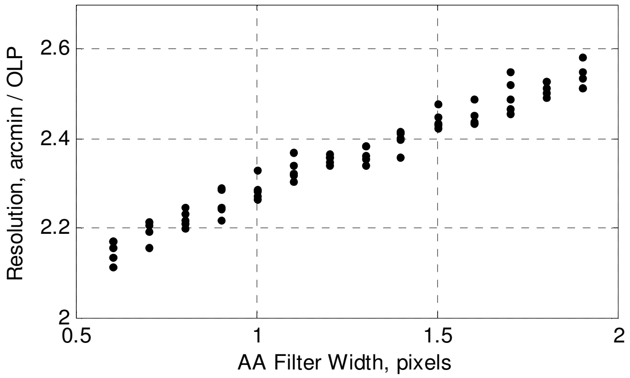

Figure 6. Display system resolution measurements as a function of antialiasing filter width (pixels). The SEM of the resolution measurements is 0.010.

TOWARDS EYE-LIMITED RESOLUTION

Over the past few decades the resolution of simulation training display systems has been limited by display system attributes such as the spatial sampling rate, video amplifier bandwidth, blurring by components such as CRTs, projection lenses, and screen diffuser coatings, IG-based antialiasing, image remapping (warping), and the misalignment of blend regions between channels. Historically, the resolution of the display system has been far lower than the "resolution limit" of the typical observer. Thus, precision of subjective measures of display system resolution has not been limited by the acuity of the observer, even though there is a substantial variation in acuity across observers.

Recall that a primary motivation for the use of an objective metric of resolution was to reduce the significant variance in the measurement method. Unfortunately, as the industry continues the move towards higher display system resolutions, the variance in the acuity of the observers conducting the test will become a larger fraction of the variance in the measurement. Thus, we find ourselves in the peculiar situation that as display system resolution improves; the precision with which we can measure it will *decrease*. In other words, the need for a low variance objective measure of display system resolution will increase as display systems improve.

ACCOUNTING FOR SAMPLING ARTIFACTS

The research described in this paper began several years ago when the results of our testing of stereoscopic display configurations suggested that depth discrimination performance can be seriously degraded when spatial sampling artifacts are present in a display system (Lloyd and Nigus 2012). In the second evaluation of that series (Lloyd 2012) we replicated our finding that stereoscopic disparity thresholds in the range of 6 arcsec can be obtained if sufficient antialiasing is performed, and provided equations indicating the magnitude of the antialiasing requirement as a function of pixel pitch.

In the third paper of the series (Lloyd 2013) a new metric of antialiasing sufficiency was described along with the results of initial testing of the metric. The proposed metric of antialiasing sufficiency uses the same test pattern, camera system, photographic procedure, and much of the same image processing software as does the display system resolution described in the present paper. Thus, both the MTF of the display system and the magnitude of the sampling artifacts can be measured using a single camera image. Figure 7 provides an illustration of the type of image processing that is used to isolate the Moiré patterns that are produced with insufficient antialiasing. The RMS magnitude of the modulation in the Moiré pattern was shown to correlate strongly ($R^2 = 0.99$) with stereoscopic depth discrimination threshold data measured as a function of antialiasing filter width (Lloyd 2012).

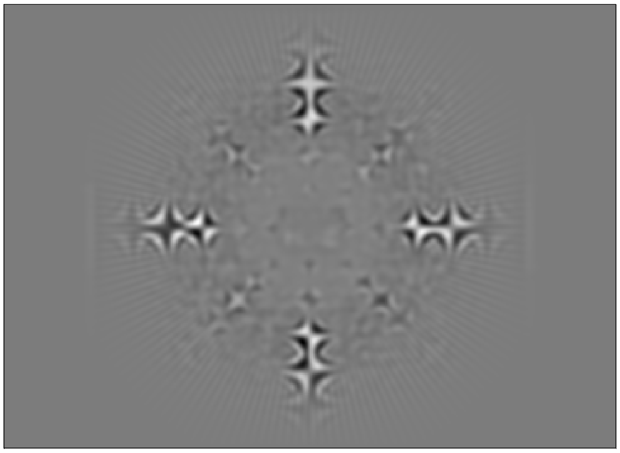

Figure 7. Filtered version of the camera image shown in Figure 3 illustrating the method of isolating the moiré pattern so that the magnitude of the sampling artifacts in the image can be quantified.

CONCLUSIONS

- Objective metrics and measurement methods for display system resolution were developed and refined beginning approximately 50 years ago.
- Objective resolution measurements were used for Air Force training programs from the mid 60s to the mid 80s and fell out of use when the Air Force ceased requiring the measurements in support of their acquisitions.
- Likely reasons the supplier community did not continue the use of the objective metrics include:
  - High cost and complexity of the early equipment
  - Impracticality of measuring from the eyepoint of completed training devices
  - Inability to account for sampling artifacts
- The cost and complexity of making objective display system resolution measurements is far lower today due to the availability of capable digital cameras, portable computers, and IG-based test patterns.
- The standard deviation of the objective resolution measurements described here was 1% of the resolution which is 1/12th of the standard deviation of the subjective estimates obtained using the JAA lightpoint size test.
- Methods of accounting for spatial sampling and sampling artifacts have matured and have been shown to correlate well with task performance.
- The measurement of both display system resolution and sampling artifacts can be made using a single test pattern and camera image.
- The variance of the subjective measures of resolution will increase as display system resolution increases.

The cost, complexity, and technical barriers to making comprehensive display system resolution measurements have been reduced to inconsequential levels. We look forward to collaborating with stakeholders in the simulation training industry to refine and validate the metric described here as well as other candidate metrics designed to meet the specific needs of the simulation training community.

STAKEHOLDER FEEDBACK

This paper describes the results of evaluations that were conducted in 2012-13 and provides a detailed description of the metric, camera, settings, and procedure that was used to collect the data presented in this paper. These details are provided so that one could replicate our findings if required. Please understand that we are NOT recommending the use of this particular combination of metric, camera, settings, and procedure for three reasons:

- This particular camera is no longer available.
- The performance/cost ratio of digital cameras has improved significantly since we purchased this particular camera, and we expect this trend to continue.
- It is premature to freeze the specifics of the metric, camera, settings, or procedure until we complete our testing and have obtained and accommodated stakeholder feedback.

In the process of publishing the results of our last two evaluations we have received important feedback from a number of people. First, several people have expressed concern with the use of the JPEG image format. We are now convinced that the advantages afforded by this format are not offset by the potential challenges it creates and the doubt it sheds on the results. We will most likely switch to the use of raw images for our next evaluation. Several reviewers have suggested that we design the test patterns and procedures such that the characterization of a simulation training device can be automated. We will attempt to accommodate this design goal in our future work and we solicit stakeholder inputs to help us refine what this means. Finally, we have been asked to explicitly consider and describe how a display system resolution metric and procedure can be applied to moving images.

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