DETERMINANTS OF SYSTEM RESOLUTION FOR MODERN SIMULATION TRAINING DISPLAY SYSTEMS

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ABSTRACT

This paper presents the results of measurements and analyses of the primary components that affect display system resolution. These components include sampling rate (angular pixel pitch), anti-aliasing filter width (sampling aperture), line spread function, image re-mapping (warp), lens blur, projection screen, and scattered light. The relative influence of each of these components on system performance is described.

With the CRT-based systems that were pervasive a decade ago, system performance was significantly limited by components such as CRT spot size, video amplifier bandwidth, and lens blurring. The performance of these components is well described using the modulation transfer-based metrics adapted from the field of optical engineering for non-sampled imaging systems. Since these projector components were primary determinants of system resolution, these measurements were a useful correlate of user performance for training display systems.

In recent years, digital display systems have come to dominate and CRT-based systems are being replaced at a rapid pace. With the newer digital display systems the traditional resolution limiters have been reduced to nearly inconsequential levels and variables such as spatial sampling, artifacts, anti-aliasing, and digital warping have become relatively more influential. Additionally, the use of substantially higher pixel counts has pushed the performance of these new systems closer to "observer-limited" performance than the systems they replace.

To accommodate these system design trends, the metrics and measurements used to evaluate system performance need to account for sampling-related characteristics if they are to remain good correlates of training task performance. Additionally, these metrics and measurements need to account for the visual capability of the observers who will use these systems.

INTRODUCTION

The tools of linear systems analysis have been used for many decades to objectively characterize the performance of electronic display and imaging systems (Schade 1951; Harshbarger 1965; Biberman 1973; Verona et. al. 1979; Infante 1985; Holst 2000; Vollmerhausen et. al. 2010). Several researchers have shown that metrics based on perceptually-weighted modulation transfer functions (MTF) are very good predictors of visual task performance and of subjective assessments of image quality and utility (Snyder et. al. 1974; Task 1979; Beaton 1984; Snyder 1985; Barten 1989; Lloyd 1990). From the mid-60s to the mid-80s, camera-based measures and MTF analysis were required as part of the display system acquisition process for the U.S. Air Force (Harshbarger 1965, Lloyd & Basinger 2013b). While these methods are no longer required by the Air Force, many of the suppliers within the simulation training industry use the tools as part of their analyses of expected system performance (Black 1998; Blackham & Wynn 2000; Lyon 2012; Harris, G. 2012).

In the late 90s, Black (1998) and his colleagues at Evans & Sutherland presented a set of MTF curves that are representative of the performance of the CRT-based simulation training display systems of that time period. These curves have been presented at many professional development courses since that time (i.e., Lyon 2012) implying they are considered to be representative of the performance of modern training display systems. These curves are presented in Figure 1, courtesy of P. Lyon.

One of the most important benefits of the MTF approach is that the performance of the display system can be predicted by multiplying the MTFs of each of the components of the system. This multiplicative property of linear imaging systems also allows the designer to determine which of the components have the largest effects on system resolution. Thus, system designers and acquisitions professionals can focus development attention and dollars on these components… or minimize the time

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and money spent attending to the components that have relatively little effect on system performance.

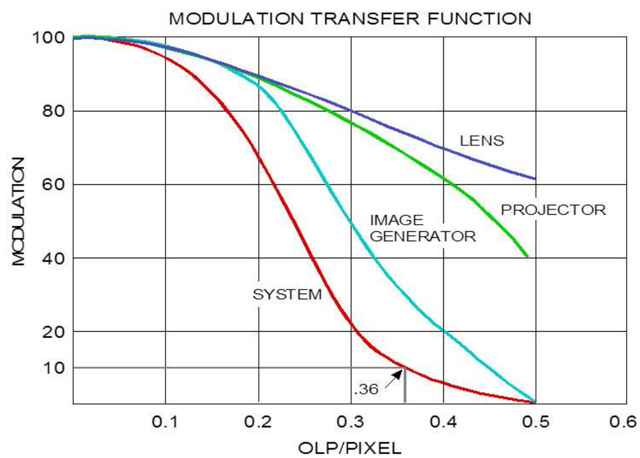

Figure 1. Modulation transfer functions for three major system components (lens, projector, and image generator) as a function of spatial frequency. From Black (1998). Figure courtesy of P. Lyon.

RELATIVE CONTRIBUTIONS

Using the data provided in Figure 1, two calculations can be made to determine the relative effects of the components on system resolution. The casual observer may look at the relative heights of the curves in Figure 1 and note that modulation transfer factors for the lens, projector, and image generator are approximately 0.75, 0.70, and 0.32 at the resolution limit of the system which is defined as occurring at the frequency that produces 10% modulation (0.36 OLP/pixel). From these numbers one may conclude that the image generator has about 0.75 / 0.32 = 2.3 times the effect on system performance than the lens, and about 0.70 / 0.32 = 2.2 times the effect of the projector. One might also conclude that the effect of the image generator is about (0.75 * 0.70) / 0.32 = 1.6 times the combined effect of the projector and lens. However, the reader is warned that this interpretation of the data in Figure 1 overestimates the relative effect of the highest curve (i.e., lens) and underestimates the relative effect of the lowest curve (i.e., image generator) on the resolution of the system.

A more meaningful method of determining the relative contributions of the components involves determining the increase in system resolution that occurs for a small increase in the resolution of each system component. This "sensitivity analysis" is performed by shifting each of the component curves to the right (increasing spatial frequency) by a small amount and re-computing the system resolution. Note that the previous analysis considered the vertical positions of the curves (modulation transfer) whereas the preferred analysis considers the effects of changes in horizontal position (spatial frequency). This calculation produced the following increases in system resolution for a 1% increase in the resolution of each system component: Lens: 0.09%, Projector: 0.20%, IG: 0.71%. These results indicate that the image generator has about 0.71 / 0.09 = 7.9 times the effect on system resolution than the lens, and about 0.71 / 0.20 = 3.6 times the effect of the projector. The analysis also indicates that the effect of the image generator is about 0.71 / (0.09 + 0.20) = 2.4 times the combined effect of the projector and lens. The results of both of these analyses are presented in Table 1.

Table 1. Relative contribution of each component to system resolution, using the casual and preferred methods of analyses.

Component	Casual Analysis	Preferred Analysis
Lens	0.23	0.09
Projector	0.24	0.20
Lens + Projector	0.47	0.29
Image Generator	0.53	0.71

These data indicate that (circa 1998) the engineer looking to make the largest gains in the performance of the system should look into the components and processes we typically lump into the category of "image generator." The projector and lens offer less opportunity for improvement in the performance of the system. When these data were collected (prior to 1999), raster-calligraphic CRT projectors and image generators custom designed for flight simulation dominated the simulation training industry. At that time, components and processes associated with the projector, such as video amplifiers, cables, connectors, and switches, electron beam spreading, and phosphor thickness and saturation were important constraints that fundamentally limited the resolution of these projectors. Due to the "Lambertian" emission of light from CRT phosphor, it was not possible to design a projection lens that simultaneously had high resolution and high lumen throughput. Due to the poor Etendue of this image source, the exotic lens features we take for granted today, such as zoom and lens shift, were clearly impractical for CRT projectors. With the advent of modern digital projectors and image transmission methods, most of these constraints on resolution have been eliminated. Thus, we expect that the relative effect on system resolution of the projector and lens would be lower for modern display systems than the proportions indicated in Table 1.

With most CRT-based display systems of the 80s and 90s, geometry correction was accomplished by modulating the electron beam deflection signals within the CRT projector. With deflection-based warping of video images, the projector resolution is reduced very little due to the geometry correction. In contrast, the digital image remapping (warp) used to correct geometry with modern display systems noticeably reduces the resolution of the system. Thus, we expect that the relative effect on system resolution of the image generator (or warp box) would be greater for modern display systems than the proportions indicated in Table 1.

RESOLUTION MEASUREMENTS

The following sections provide measurements that are representative of many of the key components and processes that occur in the modern digital display and image generation systems used for simulation training.

Projector

The measurements presented here were made using a Sony SXRD (VPL HW30ES) LCoS projector that was sold into the home theater market for approximately $2500 in early 2013. This projector was selected because it is commonly-available, inexpensive, and represents the lower end of the performance spectrum of projectors and lenses that may be used in simulation training applications. We can be confident that the resolution of the purpose-built projectors and lenses that are typically used in the simulation training industry will be at least as good as the resolution measurements reported here. This projector has a native addressability of 1920 x 1080 pixels and was operated at a frame rate of 60 Hz. The supplier data sheet reports the projector produces 1300 lumens and a sequential contrast of 70,000:1.

Screens

Two different screen samples were used in this evaluation. For the front projection conditions, the screen consisted of a 41 x 33 cm (16 x 13 in) piece of smooth white hardboard that was coated with a flat white spray paint. For the rear projection condition, a 38 x 28 cm (15 x 11 in) sample of an acrylic spherical rear projection screen was used. The thickness of this sample was 5.0 mm (0.20 in) and the coating was approximately 0.5 mm (0.02 in) thick. The radius of the screen was measured at 1.6 m (5.3 ft). The screen sample is estimated to be at least ten years old.

Camera

Measurements were made using a Canon EOS T3i consumer color camera equipped with an EFS 18-135 mm lens. Prior to the evaluation, the gray scale response of the camera was measured and a correction equation was derived that is used to linearize the grayscale response of the measurement system. The MTF of the camera was also characterized using an independent test pattern. A multidimensional correction equation was derived that is used to correct the measurements for the roll off of the camera MTF as a function of aperture and zoom settings of the camera lens. For the measurements reported in this paper the MTF of the camera lens was never less than 0.90 at the sampling limit of the display system.

Setup

The screen samples were positioned 1.9 m (76 in) from the projector and the projector zoom control was adjusted such that the line/grille pattern was 15 cm (5.9 in) high and the radial grating pattern was 22 cm (8.6 in) high. With these settings the pixel pitch of the projector was 0.74 mm (0.029 in). With these settings the peak white luminance of the system was 69 fL and the simultaneous contrast ratio was 99 for the radial grating and 140 for the line/grille pattern. The camera was mounted on a heavy tripod and positioned 1.32 m (52 in) from the screen. The camera lens was zoomed such that the radial grating pattern spanned about 90% of the vertical extent of the image. This zoom setting produced a sampling rate of at least 9 camera pixels / display pixel. For the resolution calculations presented here the observer position was assumed to be at 1.68 m (66 in) from the screen for an angular pixel pitch of 1.5 arcmin. This assumption sets the sampling limit of the display system at 20 cyc/deg (labeled "samp limit" in the figures below).

Line/Grille Pattern

Measurements of edge spread functions (ESF), line spread functions (LSF), and grille pattern contrast were made using the test pattern shown in Figure 2. This pattern was generated using the MATLAB software running on a Windows PC equipped with an Nvidia GTX 660 Ti graphics board. This pattern was 300 pixels wide and 200 pixels high. The white box in the upper left corner spanned 50 pixels and the boxes drawn with single pixel horizontal and vertical lines spanned 100 pixels. The design of the grille patterns followed from the Information Display Measurement Standard (IDMS) and consisted of seven 1-on-1-off, seven 2-on-2-off, five 3-on-3-off, and four 4-on-4-off white bars.

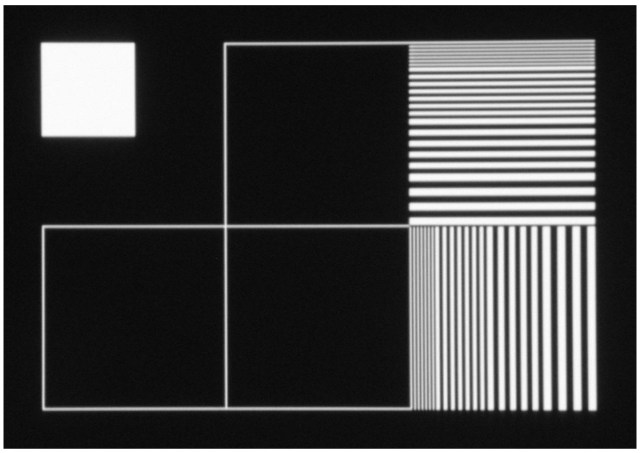

Figure 2. Photograph of the line/grille test pattern used to measure the "continuous" system components. This pattern was generated using the same computer and software as described above.

Radial Grating Pattern

In previous research a radial grating pattern was designed to support the simultaneous measurement of system resolution (Lloyd & Basinger 2013) and the magnitude of the spatial sampling artifacts (Lloyd 2013) that are present in the image. This pattern is rendered using 131 white triangular shaped polygons on a black background that are arranged in a radial pattern as shown in Figure 3. The angular width of the white polygons is 4 times that of the black spaces between the polygons for a white duty cycle of 20%. For the measurements reported in this paper, the size of the pattern was held constant at 299 pixels high. Thus, the sampling rate of the pattern was known and ranged from 0 pixels/cycle at the center to 7.2 pixels/cycle at the top, bottom, left, and right edges radial grating. Also included in this pattern are alignment marks (small black squares with white surrounds), a camera focus pattern at the center, and ten gray scale patches used to verify that the electro-optical response (gamma) of the display system was linear at the time the resolution measurement was made.

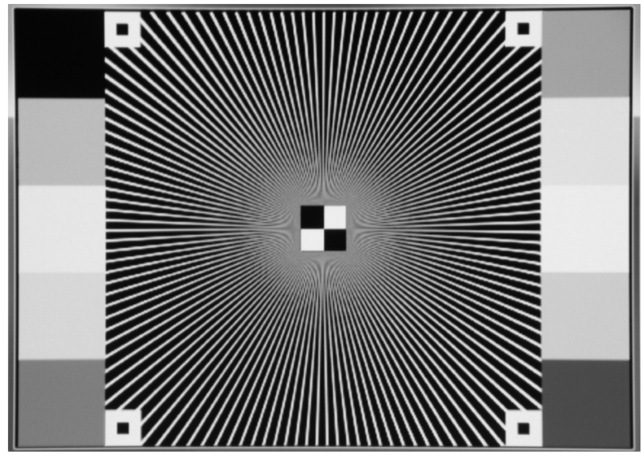

Figure 3. Photograph of the radial grating test pattern used to measure the resolution of all components of the display system.

"CONTINUOUS" MEASUREMENTS

The field of optics has provided us with several objective measures for characterizing the resolution of those display system components that can be fairly characterized as non-sampled or spatially-continuous systems. For example, edge-spread and line-spread functions have often been used to characterize display components such as projection lenses, CRT spot size, video amplifier bandwidth, and the blurring caused by screens and mirrors.

Edge Spread Function

An edge spread function (ESF) measurement was made for the Sony projector using a calibrated photograph of the line/grille test pattern shown in Figure 2. For this measurement a luminance scan positioned horizontally across the white square in the upper left corner of the image was extracted. This luminance scan was differentiated to obtain the rate of change in luminance as a function of distance across the edge(s). The mean of the rising and falling edges of the pattern were averaged together and are presented in Figure 4. For this measurement the projector was well focused on the front projection screen. Relative to the other three resolution measures discussed in this paper, the ESF describes the effects of the smallest number of components that contribute to resolution loss within the system. As measured here, the ESF accounts for the combined effects of the projection lens, screen, and any other processing, blurring, or pixel cross-talk that may be due to the electronics, cables, or display panel. The MTF computed from this function is presented in Figure 6.

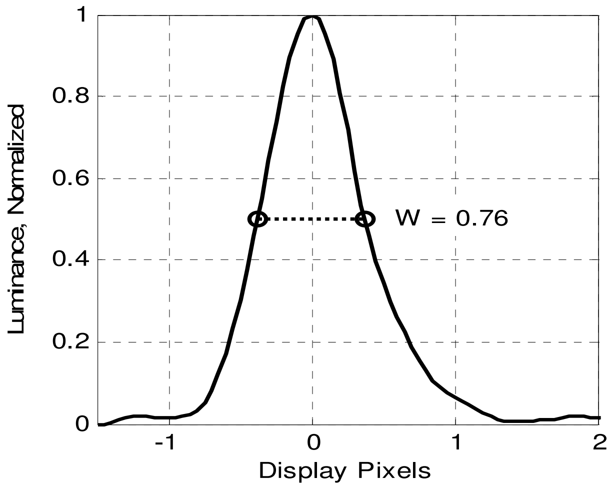

Figure 4. First difference of the edge spread function (ESF) for a horizontal luminance scan across the vertical edges of the white square in the upper left corner of Figure 2. The half-maximum width of this function was 0.76 pixels.

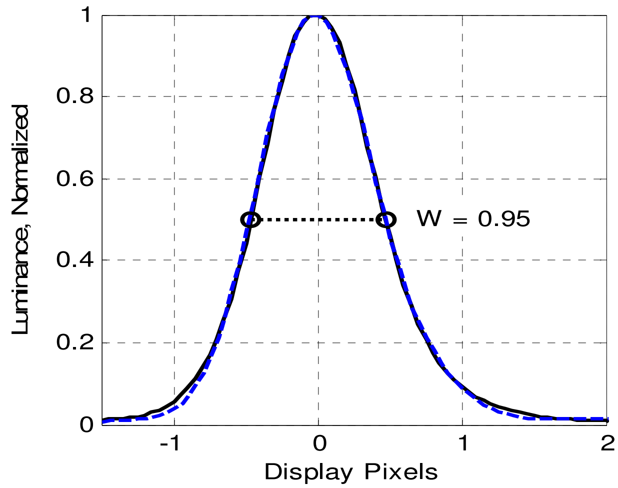

Figure 5. Measured line spread function (LSF) is shown as the solid black line. The dashed blue line shows the result of convolving the ESF from Figure 4 with a rectangular "pixel aperture" with a width of 0.72 pixels.

Line Spread Function

A line spread function (LSF) was extracted from the calibrated image shown in Figure 2 using the vertical white line in the lower half of the pattern. The measured LSF is plotted in Figure 5 as a solid black line with a half-maximum width of 0.95 pixels. Also plotted in Figure 5 (blue dashed line) is the expected LSF that was calculated by convolving (blurring) a rectangular "pixel aperture" of width 0.72 pixels with the edge spread function shown in Figure 4. The close correspondence between the predicted and measured LSFs illustrates the fact that the LSF accounts for one additional source of resolution loss within a display system than does the ESF. The LSF includes all of the contributions that the ESF includes plus the effect of the pixel aperture. The MTF calculated from this function is presented in Figure 6.

Grille Pattern

With the recent publication of the long awaited Information Display Measurement Standard (IDMS), (SID 2012) it seems likely that the Grille Pattern method might be considered for evaluating the performance of simulation training display systems. A decade ago a modified version of this measurement procedure (VESA 2001) was recommended by Geri et. al. (2004) for evaluating flight simulator visual displays.

The response of the display system to the grille pattern was measured by extracting a horizontal luminance scan across the center of the lower grille pattern shown in Figure 2. This luminance scan was then convolved with a rectangular kernel the size of one display pixel (11 camera pixels) as per the procedure described in Section 7.2 of the IDMS. The minimums and maximums of the filtered luminance scan were then used to calculate the modulation for each of the four frequencies in the pattern. The results of this calculation are shown as red boxes in Figure 6.

While these data are plotted together with the MTFs derived from the ESF and LSF, the reader is warned that they should not be interpreted as an MTF. The grill pattern approach does not produce a continuous function; rather, it produces four discrete data points that are affected by both the ESF of the display as well as the pixel aperture in a complex way that is not equivalent to an MTF. The grille pattern approach over-estimates the modulation of the display for the middle and low frequencies. The reader is warned that the grille pattern method was developed as a simple method for making comparisons between direct view flat panel display devices. It is not a display *system* metric because it does not account for the sampling-related factors that are the primary determinants of display system resolution.

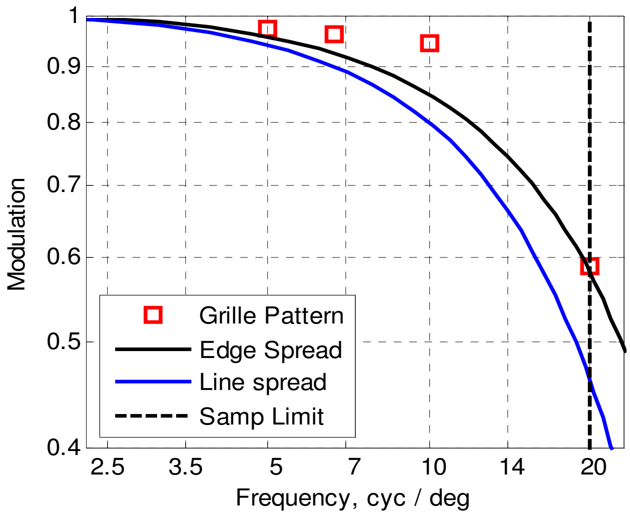

Figure 6. Modulation Transfer Functions computed from the Edge Spread Function shown in Figure 4 and the Line Spread Function shown in Figure 5. The red boxes indicate the modulations measured at four discrete frequencies using the grille pattern method.

Effect of Mis-Convergence

Figure 7 shows a close up photograph of the intersection of the horizontal and vertical white lines in Figure 2. When this image was captured, the projector was well converged in the horizontal direction and clearly mis-converged in the vertical direction. The observer could see a distinct red-green separation for horizontal lines. To measure the effect of this mis-convergence, a LSF was extracted across the horizontal line and is plotted in Figure 8. For comparison, the LSF for the well-converged line (from Figure 5) is also plotted in Figure 8. To quantify the difference between the well-converged and mis-converged conditions, the MTF was computed for the mis-converged condition and divided by the MTF for the well-converged condition. The resulting MTF is plotted in Figure 9.

Effects of Screen, Focus, and Washout

The effects of three additional variables were computed in much the same way as the effect of mis-convergence. The effect of switching to the rear projection (RP) screen was measured by substituting screens (and changing the camera position), measuring the LSF, and computing the MTF. The MTF for the RP condition was divided by the MTF for the front projection condition to obtain the curve plotted in Figure 9.

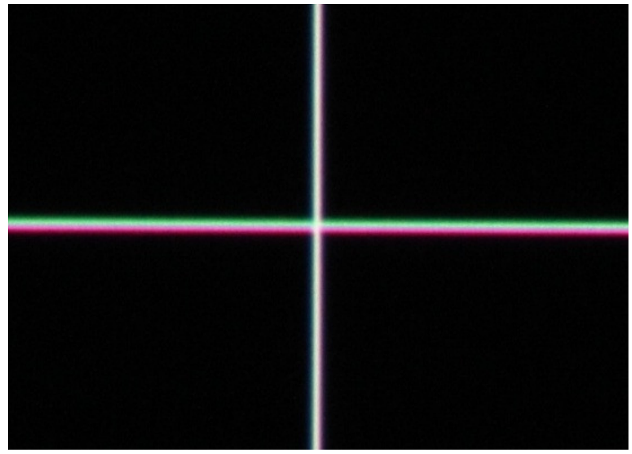

Figure 7. Close up photograph of the line intersection from Figure 2 illustrating the distinct color mis-convergence occurring in the vertical direction.

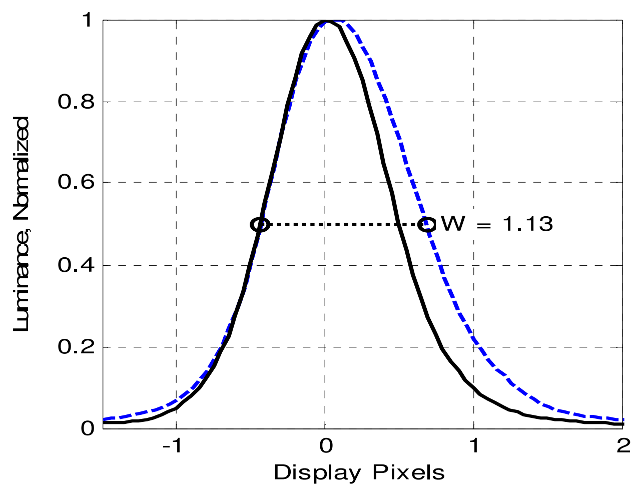

Figure 8. Line spread functions for the mis-converged horizontal line and the well converged vertical line in the line/grille pattern shown in Figure 7.

For the mis-focus condition, the front projection screen was used and the projector lens was mis-focused to the point where an observer could clearly detect the increased blurring of the lines from a distance of 1.68 m (pixel pitch = 1.5 arcmin). With this amount of blur, the column and row lines between adjacent pixels were no longer discernible whereas they were clearly discernible for the well-focused condition. The MTF quantifying the effect of mis-focusing the projector is presented in Figure 9.

For the "washout" condition a constant veiling luminance was added to the image of the test pattern that reduced the contrast ratio to 10:1 at low frequencies which is representative of the contrast attained in many simulation trainers for daylight scenes. The effect of this scene contrast reduction is shown as the pink dashed horizontal line in Figure 9 at a modulation of 0.835 which accounts for the change from 100:1 contrast to 10:1 contrast.

For comparison, the MTF representing the effects of the projector and lens (LSF from Figure 6) is provided. Recall that for this measurement the projector was well-focused and converged, had > 100:1 contrast, and was measured using the front projection screen.

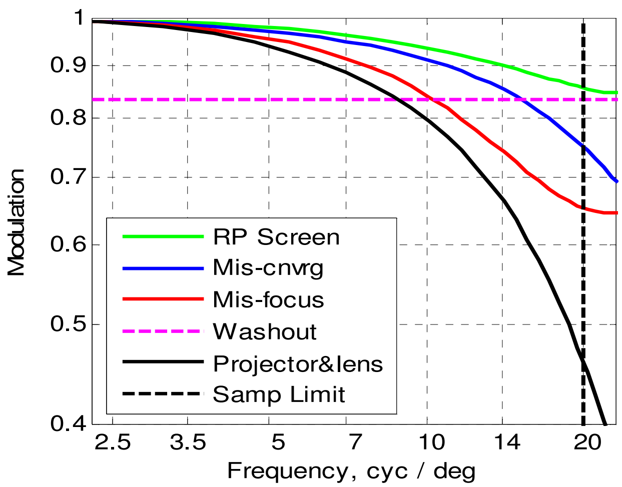

Figure 9. The black solid curve indicates the projector MTF under optimal conditions. The remaining curves show the reductions in MTF caused by the RP screen, mis-convergence, mis-focus, and washing out the image to a contrast ratio of 10:1.

SAMPLING-RELATED MEASURES

The three measurement methods described in the previous section, ESF, LSF, and Grille Pattern have been used for many years to objectively evaluate the performance of display devices and those portions of display systems that can be fairly represented as "continuous" or non-sampled in the spatial domain. Recall that to make these measurements the test pattern must be lined up perfectly with the pixel structure of the display device. With training applications, however, image features are arbitrarily scaled and rotated and can be positioned anywhere within the FOV, thus, they are positioned essentially randomly relative to the pixel structure of the display. From this it follows that if we wish to characterize the performance of the system, we must make the measurements with the test pattern arbitrarily translated, rotated, and scaled relative to the pixel structure of the display.

The challenge of theoretically accounting for the sampling-related characteristics of display systems has been addressed in many technical papers and several texts that thoroughly cover the topic. The reader interested in delving more deeply into this complex compartment of mathematics is referred to Park et. al. (1984), Fliegel (2004), Vollmerhausen et. al. (2000), and Holst (2000). While these authors provide a solid mathematical treatment of the subject, they do not describe practical methods for *measuring* display systems that account for sampling, re-sampling, artifacts, and anti-aliasing.

If one wished to apply this mathematical approach, they would need to know many system design details such as the sampling aperture, anti-aliasing filter width, pre-warp sampling rate, reconstruction filter characteristics, post-warp sampling rate, and display line spread function. These design details are generally unavailable to simulator certification professionals; thus, the mathematical approach is unsuitable for supporting the acquisition process.

The resolution measurement procedure, metric, and analysis described by Lloyd & Basinger (2013) were developed to allow the measurement of the net effect of all sources of resolution loss within a system, without requiring suppliers to reveal many details of their system design. Using the radial grating test pattern shown in Figure 3 and a calibrated camera, the evaluator can measure MTFs for thousands of combinations of pattern phase and orientation using a single camera image. The results of prior testing demonstrate that the method produces resolution measurements with a standard deviation of about 1% of the mean. The method is precise enough that it can be used to discriminate the differences between antialiasing filter widths and alternate pixel remapping (warp) algorithms.

System MTF

The MTF of the display system was measured using the radial grating pattern and associated methods for capturing and analyzing the image (Lloyd & Basinger 2013). For this measurement an antialiasing filter width of 0.8 pixels was applied and the image was warped using the bi-cubic interpolation function in MATLAB. The projector was well focused and converged and reflected from the front projection screen sample. The measured system MTF is shown in Figure 10 (lowest curve) along with the measurement results provided in Figure 9. As expected, the MTF of the system is much lower than the MTFs for the five "continuous" variables measured above. The large reduction in system resolution is attributable to the fact that the image is spatially sampled, antialiasing is applied, and the image has been re-mapped (warped). Clearly, the effects of the sampling-related variables are much larger than the effects of the "continuous" variables (upper black solid curve).

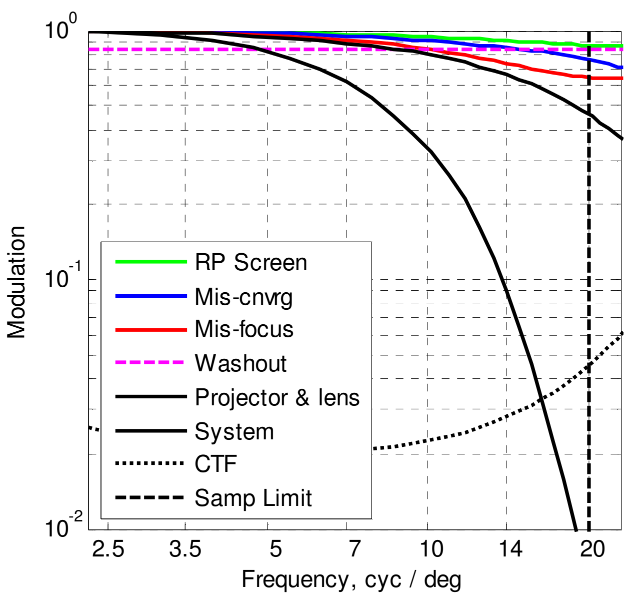

Figure 10. The lower black solid curve indicates the MTF of the display system with an antialiasing filter width of 1.1 pixels, bi-cubic image warping, and a well focused and converged projector on the front projection screen. The five curves shown in Figure 9 are included for comparison.

Limiting Resolution

The limiting resolution of the display system is computed using the contrast threshold function (CSF) which describes the contrast required by the observer (Barten 2000). Following the well-tested methods of Charmin & Olin (1965), Snyder (1985) and others, the limiting resolution of the display system is defined as the spatial frequency at which the CSF and the display system MTF intersect. For the example in Figure 10 the limiting resolution is at 16.3 cyc/deg.

Effects of Antialiasing and Image Warping

The effect of changes to the antialiasing filter width were determined by measuring the system resolution with the antialiasing filter width set to three levels, 0.5, 0.8, and 1.1 pixels. The narrowest filter setting was determined to be "clearly insufficient" for the purpose of antialiasing stereoscopic (3-D) images while the widest setting was determined to be "clearly sufficient" (Lloyd, 2012). Changing from the center to the narrowest filter increased system resolution by 2.4% while changing to the widest filter reduced system resolution by 3.7%.

The effect of changes to the type of image warping applied was determined by measuring the system resolution for three settings of the warp algorithm: None, bi-cubic, and bi-linear. Changing from the bi-cubic to none setting increased the system resolution by 4.2% and changing from the bi-cubic to the bi-linear setting decreased system resolution by 3.9%.

Effects of Projector and Lens

The effect of changing the resolution of the projector and lens was re-calculated using the MTFs shown in figure 10 and using the CTF, rather than the 10% modulation criterion, to determine the limiting resolution of the system. Results of this analysis indicated that a 1% change in the projector & lens resolution produce a 0.011% change in the system resolution. Note that the effect of the projector & lens for the CRT system of 1998 was 2.6 times greater than this.

While not measured directly, the separate effects of the projector and lens were estimated using the proportions obtained for these two components using the 1998 data. The right column of Table 3 indicates these estimates which are 7% for the projector and 4% for the lens.

SUMMARY AND CONCLUSIONS

As expected, the data and analyses presented here indicate that the opportunity for improving display system resolution by improving the resolution of the projector-related components is significantly lower for contemporary digital display systems than it was for the CRT-based systems of the late 1990s. This finding suggests that designers and acquisitions professionals should pay increased attention to improving the "sampling related" components of the display and image generation system which have an effect that is approximately 8 times larger than the combined effects of the projector & lens.

Table 3. Relative contribution of each component to system resolution for a well focused projector on the front projection screen, bi-cubic warping, and good antialiasing.

Component	1998	2014
Projector & Lens	0.29	0.11
Projector	0.20	0.07*
Lens	0.09	0.04*
Image Generator	0.71	0.89
Spatial Sampling	-	0.79
Antialiasing (good)	-	0.06
Warping (bi-cubic)	-	0.04

Table 4. Reduction in system resolution due to changes in selected components.

Component	Reduction
Rear projection screen	2.5 %
Color mis-convergence	3.6 %
Washout to 10:1 contrast	4.5 %
Lens mis-focus	6.9 %

This estimate of the relative effect of the sampling-related components of modern digital display systems is probably underestimated because the analyses does not consider the effects of all of the processes that occur within image generators that can reduce resolution (e.g., texture mapping) and the projectors and lenses typically used in simulation training applications are expected to perform better than the components selected for this evaluation.

To date we have found no papers or technical reports that describe practical and affordable methods for objectively measuring display system resolution that can be used to support the acquisition process. The common text books describing display design and measurement do not address the sampling-related attributes of these systems (Keller 1997; MacDonald & Lowe 1997; Stupp & Brennesholtz 1999; Hainich & Bimber 2011). The IDMS (2012) describes several methods for measuring resolution at the display pixel level, but do not address the system level effects of the sampling related components. While many papers and texts mathematically address the effects of these sampling related components, the complex analyses and many design details required to employ this approach make it impractical for the acquisition process.

A practical and affordable method (test pattern, measurement procedure, and analysis) for measuring system resolution was presented at the IMAGE 2013 conference (Lloyd & Basinger 2013). This method was designed to evaluate the net effect of all sources of resolution loss within an image generator and display system. The results of subsequent testing of this method indicate the precision of the method is sufficient to discriminate between small changes in the antialiasing filter width and between different methods of resampling (warping) images.

BIOGRAPHY

Dr. Charles J. Lloyd is president of Visual Performance LLC where he addresses research and development challenges relating to training display system design, requirements, metrics, and measurements. He has 28 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 75 papers in this arena.

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