Contrast Sensitivity Experiment to Determine the Bit Depth for Digital Cinema

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The SMPTE Color ad hoc group was formed in 2001 (under DC28.2) to investigate the colorimetric requirements for the Digital Cinema Distribution Master (DCDM). A draft specification on color image encoding was published in September 2002 that recommended the use of XYZ color space, a gamma 1/2.6 transfer function, and 12 bits per color. With the support of Digital Cinema Initiatives (DCI), a test was designed to verify these color image encoding parameters. This paper reports the results of the contrast sensitivity experiment, which showed that many of our observers could see a modulation corresponding to a one code value change with 10-bit encoding, but few observers would see a one-code value change with 12-bit encoding. This result matches the results of published contrast sensitivity experiments.

In order to encode the color information in an image for the Digital Cinema Distribution Master (DCDM) a number of parameters need to be standardized. The parameters that have received the most attention from the DC28 standards committees are (1) the chromaticity coordinates of the primaries, (2) the chromaticity coordinates of the white point, (3) the encoding equation, and (4) the bit depth. All parameters must be considered carefully if image artifacts are to be avoided. However, the bit depth and encoding equation are the most important parameters when trying to avoid the artifact known as contouring. The contouring artifact looks like a stepped brightness ramp when a smooth ramp was intended. It occurs when a one-code value difference in adjacent image areas is visible. To avoid the contouring artifact, the code values must have sufficient bit depth such that code values that differ by one will encode changes in luminance that are below the threshold of visibility. Because the relationship between the code values and the luminances encoded by those code values is defined by the encoding equation, both bit depth and the encoding equation are important in avoiding the contouring artifact. This paper will describe the reasoning that led to the recommendations on bit depth and the encoding equation. In addition, it will describe the experiment that was run to verify the theoretical data used in making these recommendations.

The parameter measured in vision research that gives the most information about contouring artifact is called the contrast sensitivity function (CSF). The CSF is the reciprocal of the minimum modulation that can be seen by an observer. Given a sinusoidal luminance pattern that varies either spatially or temporally, the modulation is given by

$$m = (L_{high} - L_{low})/(L_{high} + L_{low}) \qquad (1)$$

where m is the modulation, L_{high} is the highest luminance in the sinusoidal luminance pattern, and L_{low} is the lowest luminance in the sinusoidal luminance pattern. Equation 1 can be simplified by defining ΔL as

$$\Delta L = L_{high} - L_{low} \tag{2}$$

and noting that

$$(L_{high} + L_{low}) = 2 * L_{ave} \tag{3}$$

where L_{ave} is the average of the highest and lowest luminances in the sinusoidal luminance pattern. Then

$$m = (1/2) * \Delta L / L_{ave} \tag{4}$$

CSF is the reciprocal of the minimum visual modulation, m_{min}

$$CSF = 1/m_{min} \tag{5}$$

The above equations apply for a situation in which the patterns presented to the observer are sinusoidal patterns. In these experiments, the limit are operated in terms of bit depth of what a digital projector can do today. Therefore, there were not enough bits to make good sinusoidal patterns, so square waves were used. In peak-to-peak amplitude, the fundamental Fourier component of a square wave exceeds the square wave itself by a factor $4/\pi$, approximately 27%, as shown in Fig. 1.

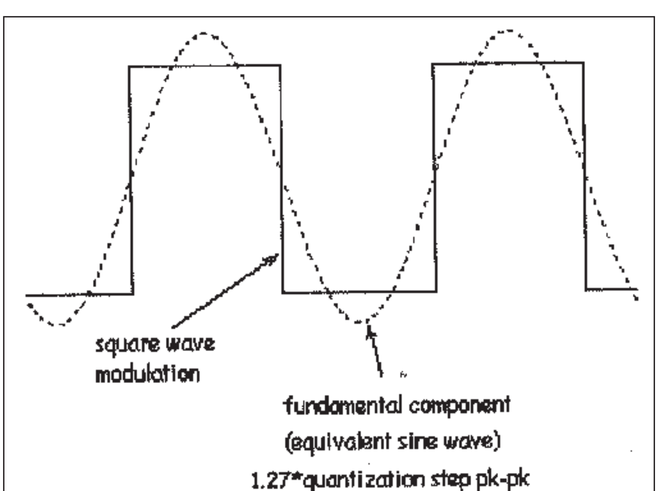

Figure 1. A square wave and the fundamental Fourier component of that square wave.

In order to fairly compare the results from square waves to the results from sine waves, the modulation for a square wave pattern therefore has to be adjusted by a factor $(4/\pi)$.

$$m = (1/2) * (4/\pi) * \Delta L_{squarewave} / L_{ave} \tag{6}$$

where $\Delta L_{squarewave}$ is the difference in luminance in the square wave as defined by Equation 2. All of the square wave modulations in this report have been corrected with this $(4/\pi)$ factor. If the minimum modulation threshold, m_{min}, is known, Equation 6 can be rearranged to give the minimum visible $\Delta L_{squarewave}$

$$\Delta L_{squarewave} = 2 * (\pi / 4) * m_{min} * L_{ave} \tag{7}$$

To interpret the experimental results, it is assumed that if the $\Delta L_{squarewave}$ is greater than the change in luminance when the digital cinema encoding code value increases by one; contouring will not be visible in a projected image.

CSF and m_{min} are dependent on a number of variables. Barten has recently published a book[1] summarizing much of the published work on contrast sensitivity function and has derived an equation that will predict the CSF as a function of the various parameters. The DC28 committees have generally accepted the work by Barten as a starting point for predictions of whether any encoding equation and bit depth would lead to visible contouring in digitally projected images in a dark theater.

Because of the importance of the Barten equation parameters, it will be summarized here. The equation numbers from Barten's book are given, with each of the equations listed here. The spatial contrast sensitivity function is given by the equation (Barten Equation 3.26):

$$CSF(u) = \frac{M_{opt}(u)/k}{\sqrt{\frac{2}{T}\left(\frac{1}{X_0^2} + \frac{1}{X_{max}^2} + \frac{u^2}{N_{max}^2}\right)\left(\frac{1}{\eta p E} + \frac{\Phi_0}{1 - e^{-(u/u_0)^2}}\right)}} \tag{8}$$

M_{opt} is the optical MTF (Barten Equation 3.6):

$$M_{opt}(u) = e^{-2\pi^2\sigma^2u^2} \tag{9}$$

σ is the standard deviation of the line-spread function (Barten Equation 3.7)

$$\sigma = \sqrt{\sigma_0^2 + (C_{ab} d)^2} \tag{10}$$

σ_o is a constant, C_{ab} is the spherical aberration of the eye, and d is the pupil diameter. The equation for d is (Barten Equation 3.9)

$$d = 5 - 3\tanh(0.4 \log L X_o^2 / 40^2 \tag{11}$$

E is the retinal illuminance in Trolands. The equation for E is (Barten Equation 3.16)

$$E = \frac{\pi d^2}{4} L\{1 - (d/9.7)^2 + (d/12.4)^4\} \tag{12}$$

In Equation 8, k is the signal-to-noise ratio of the eye, T is the integration time of the eye, X_0 is the angular size of the object image, X_{max} is the maximum angular size of the integration area, N_{max} is the maximum number of cycles over which the eye can integrate the information, η is the quantum efficiency of the eye, p is the photon conversion factor, ϕ_o is the spectral density of neural noise, and u_0 is the maximum frequency of lateral inhibition. The parameters that Barten recommended for the calculation are listed below. Because X_0 was a variable in every experiment to which Barten compared the results of calculations with his equation and the actual measured results, he did not recommend a particular value of X_0 to use.

$k = 3.0$	$T = 0.1$ sec	$\eta = 0.03$
$\sigma_o = 0.0083$ *arc* deg	$X_{max} = 12$ deg	$\phi_o = 3 \times 10^{-8}$ sec deg^2
$C_{ab} = 0.0013$ *arc* deg/*mm*	$N_{max} = 15$ *cycles*	$u_o = 7$ *cycles*/deg

For the purposes of these calculations, the committee agreed to use a value of 1.285×10^6 photons/sec/deg^2/Td as the value of the parameter p.

Therefore, the factors that can be varied in a calculation are the frequencies, u, the luminance, L, and the field of view, X_0.

The product of u, the cycles per degree, and X_0, the number of degrees, gives the number of cycles in a pattern, in this experiment 13 cycles. Therefore, X_0 can be made a variable dependent on u

$$X_o = 13/u \tag{13}$$

Thus, Equation 8 can be reduced to two independent variables, the luminance, L, and the spatial frequency, u. Because the committee wanted to be certain that no contouring would occur, we decided to calculate the spatial contrast sensitivity function, CSF(u), at a range of frequencies, u, and select the CSF value that gave the maximum value. Except for very low luminance levels, where vision is in the mesopic or scotopic region and Equation 8 does not strictly apply, the maximum value of CSF occurs in the frequency range of 1 to 5 cycles per degree. Therefore, it has been common to calculate the maximum CSF as a function of L and plot the inverse of CSF, which is the visual modulation threshold, as a function of L. Such a plot is shown in Fig. 2. If the change in luminance for a one-code value change in the DCDM encoding system falls below this modulation threshold, it is assumed there will be no contouring present in any image.

Therefore, the next task was to determine the change in luminance for all one-code value changes over the code value range of the DCDM encoding. At the time of this experiment, the DC28 committee was considering an encoding equation of the form

$$CV = (2^n - 1) * (L/P)^{(1/2.6)} \tag{14}$$

where CV is the encoding code value, n is the bit depth of the encoding, L is the luminance in cd/m^2 if all three code values are equal, and P is the peak luminance represented by code value $2^n - 1$. Although P is still a matter of discussion, at the time of this experiment, P was 41 cd/m^2. The inverse equation is

$$L = P * (CV/(2^n - 1))^{2.6} \tag{15}$$

From Equations 6 and 15 and a series of code values that vary by one, the minimum modulation that can be encoded by the DCDM equations can be calculated. These calculated minimum modulations are also plotted on Fig. 2.

Figure 2 shows that the 10-bit encoding modulation line is above the visual modulation threshold over most of the luminance range of projected digital images and thus might show contouring. However, the 12-bit encoding modulation line is below the visual modulation threshold for all luminances and should not show contouring. There are, however, reasons to question the applicability of the calculated visual modulation threshold in Fig. 2. Most images will have some random

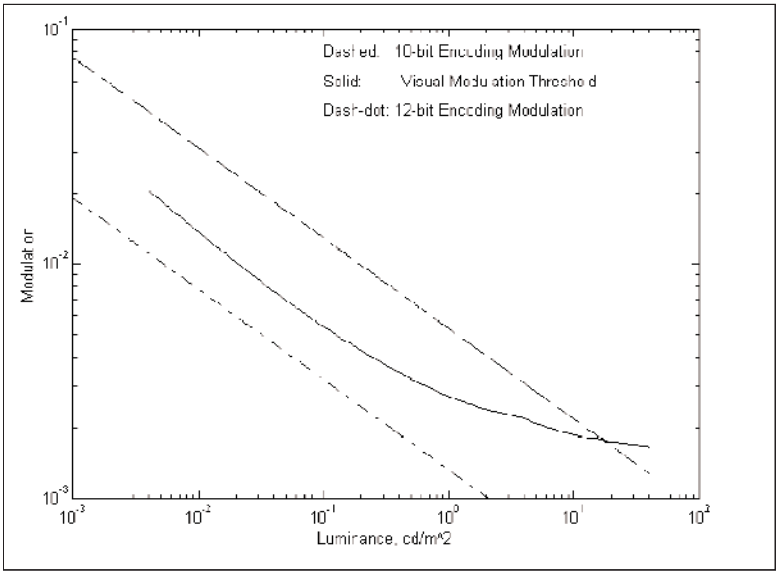

Figure 2. Modulation threshold calculated by the Barten equation and minimum modulations for 10-bit and 12-bit DCDM encoding.

luminance fluctuations (grain or noise), and this noise will raise the visual modulation threshold. The level of that noise will depend on the source material and the processing that was done in order to generate the final images. The calculated visual modulation threshold is derived from an equation that is based on laboratory condition experiments, where the influence of noise in the image is minimized. It was questionable, as to whether or not those very carefully controlled experimental conditions would be similar to the conditions of projecting digital images in a motion picture theater. In demonstrating that his equation will fit the experimental data for a large number of published experiments, Barten had to adjust the values of the k, η, and σ_o variables. The values of these variables recommended by Barten were used, but because there are variations in the values of each of the variables, it is not clear what percentage of the population will be above or below the visual modulation threshold shown in Fig. 2. Therefore, it was felt that an experiment should be conducted in a motion picture theater using a digital projector, with a large number of observers in order to determine the visual modulation threshold under the conditions of interest here.

Figure 2 also shows why the gamma 1/2.6 was chosen for the DCDM encoding equation. The slope of the 10-bit and 12-bit encoding modulation lines is determined by the value of gamma. The value chosen, 1/2.6, matches the slope of the visual modulation threshold curve reasonably well over the luminance range found in motion pictures. This then reasonably distributes the modulation for one-code value changes across the entire luminance range. One objective of the DCDM encoding equation was to be reasonably efficient in the encoding of luminance. Figure 2 shows that the encoded luminance range is longer than the aim luminance range of 0.0041 to 41 cd/m² (10,000:1 dynamic range).

Experimental Design

The experimental design chosen was very similar to what has traditionally been done in experiments to determine the threshold of human visibility. A two-alternative-forced-choice design was chosen. Each image was a uniform gray background with a square area with 13 square waves of a defined modulation and a defined average luminance. There were three average luminance levels, and within each level, there were six different modulations, and each combination of luminance and modulation was shown six times: three times as a vertical and three times as a horizontal set of square waves. The square waves with a given average luminance were shown as a group so that people were adapted to that level of illumination. Within each group of 36 images, the orientations and modulation levels were presented in random order. This order was different when the average luminance level changed. The same random order for an average luminance level was shown to all of the observers.

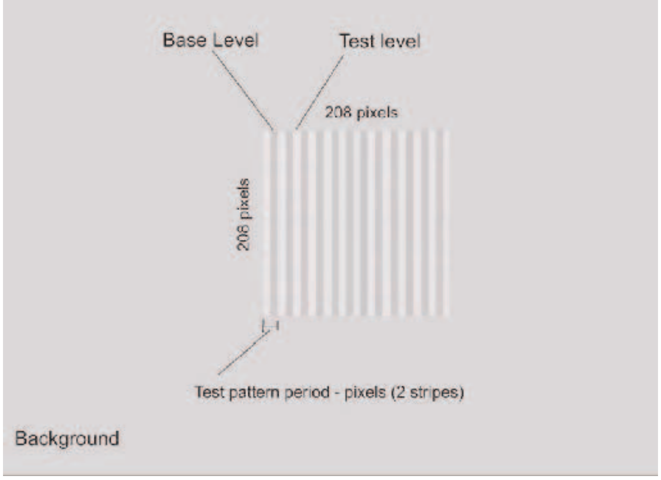

Figure 3. Illustration of a vertical square wave test pattern.

Table 1—Average Luminance Levels, Modulations, and Percent of Orientations Correctly Identified by the Observers

Luminance	Modulation	% Correct All Observers	% Correct Group 1 1.3 screen heights	% Correct Group 2 2.0 screen heights	% Correct Group 3 2.8 screen heights	% Correct Group 4 3.9 screen heights
0.279	0.00285	50.5	54.6	53.4	50.5	50.5
0.279	0.00554	69.3	74.6	65.5	63.6	65.7
0.279	0.00823	87.1	90.2	94.4	72.2	85.7
0.279	0.01104	88.5	94.3	84.7	75.0	87.8
0.279	0.01648	93.6	94.7	96.3	88.0	93.3
0.279	0.02189	96.6	96.0	98.2	94.3	97.9
3.02	0.00110	55.1	60.2	50.5	59.3	50.5
3.02	0.00220	67.9	72.1	68.2	68.4	61.1
3.02	0.00330	82.5	82.7	90.9	79.2	79.5
3.02	0.00439	88.0	90.4	90.9	79.5	88.6
3.02	0.00659	96.5	95.3	98.5	94.7	98.2
3.02	0.00878	97.2	98.3	99.5	96.3	94.7
33.8	0.00131	62.3	63.4	53.0	61.0	66.4
33.8	0.00174	75.0	74.6	71.9	75.3	77.1
33.8	0.00218	82.8	81.6	81.8	79.2	87.2
33.8	0.00261	89.6	88.5	98.5	90.7	85.7
33.8	0.00348	96.4	95.4	95.5	96.1	98.4
33.8	0.00522	98.2	97.7	99.5	98.7	97.6

Table 1 shows the three average luminance levels and the six modulation levels in the experiment.

The square waves had 8 pixels at the high luminance level and 8 pixels at the low luminance level for a total of 16 pixels per square wave. A sample vertical square wave test pattern is shown in Fig. 3. With 13 square waves, the total number of pixels in the square wave pattern was 208. In order to prevent observers from gaining any information about the square wave orientation, based on the size of the square wave image, the square waves were made 208 pixels long. This produced a square image on the screen that gave no information as to the square wave orientations. The pixel size as projected on screen (including the small black area around the image area of a pixel) is a square with edges 0.231-in. long. From these dimensions, the number of pixels per square wave and the distance of each person from the screen; the visual angles subtended by the square wave images; and the frequency in cycles per degree could be calculated. These were needed in order to calculate the modulation threshold from Equations 5 and 8. The calculated thresholds and the experimentally determined thresholds are reported in Table 2.

Table 2—Minimum Modulation Thresholds from Experiment

Luminance	Group	This Experiment, Equation 16	90% Confidence Interval	Calculated Threshold
0.279	All	0.0067	0.0035	0.0082
0.279	1	0.0059	0.0017	0.0050
0.279	2	0.0063	0.0020	0.0067
0.279	3	0.0102	0.0009	0.0090
0.279	4	0.0071	0.0028	0.0121
3.02	All	0.0029	0.0005	0.0032
3.02	1	0.0027	0.0002	0.0024
3.02	2	0.0026	0.0008	0.0027
3.02	3	0.0034	0.0005	0.0033
3.02	4	0.0032	0.0007	0.0042
33.8	All	0.0019	0.0002	0.0020
33.8	1	0.0019	0.0002	0.0019
33.8	2	0.0019	0.0002	0.0019
33.8	3	0.0019	0.0003	0.0020
33.8	4	0.0018	0.0003	0.0022

The practical method for creating the required

modulation levels using the DLP projector is described in Appendix A.

Each observer made 36 judgments at each of three luminance levels for a total of 108 judgments. The observers were asked to indicate whether they saw horizontal or vertical square waves. They made their selection by pressing either a 1 or a 3 on a keypad, which was connected to a radio transmitter that sent the individuals' scores to a receiver. This gave instant recording of the scores and entered them directly into a computer so that no transcription errors were made.

Results and Analysis

There were four judging sessions, the morning and afternoon of October 9, 2003, and two sessions on the morning of October 15, 2003. The participants in the sessions on October 9 were SMPTE DC28 members, studio people, and cinematographers. Most of these participants were older but more experienced in looking at images in a dark theater. The partici pants in the sessions on October 15 were college students or people taken voluntarily off the street in front of the Entertainment Technology Center, and all were in the age range 20 to 30. Participants in session 2 on October 15 had also been in session 1 on October 15—they participated in the experiment twice. This then represents a younger and less experienced set of observers. If the participants on October 15 who took part in both sessions 1 and 2 were counted as two "people," a total of 92 people participated in the experiment.

Based on the theory used to analyze the observers' judgments, it is clear that they should have been able to identify correctly the orientation of the two highest modulation square wave images at each luminance level 100% of the time as shown in Figs. 4, 5, and 6. Therefore, any observer who could not correctly identify the orientations of the two highest modulation square wave images at least 80% of the time were dropped from the analysis of that luminance level. After these

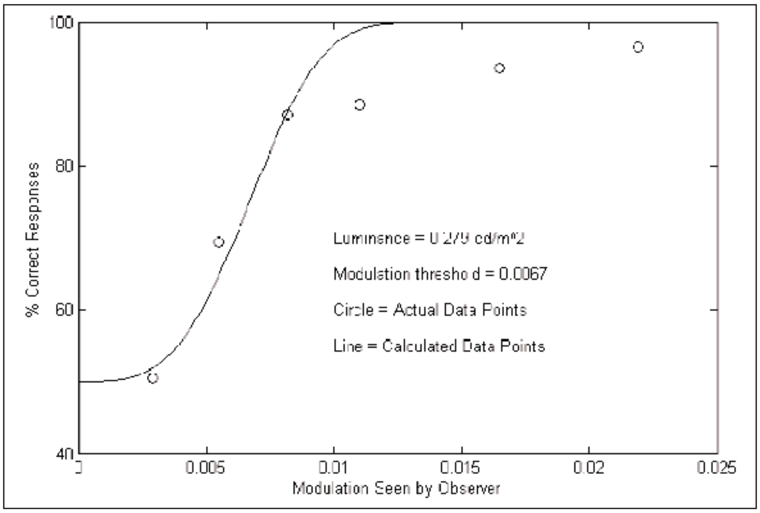

Figure 4. Determination of the modulation threshold for the 0.279 cd/m² luminance level.

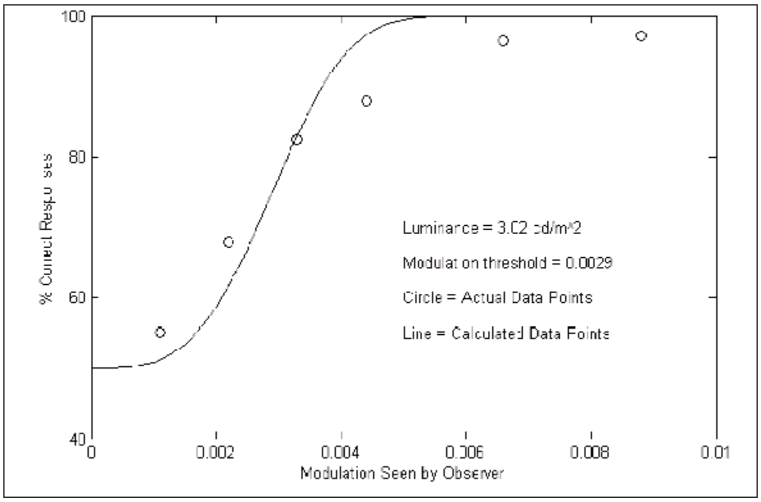

Figure 5. Determination of the modulation threshold for the 3.02 cd/m² luminance level.

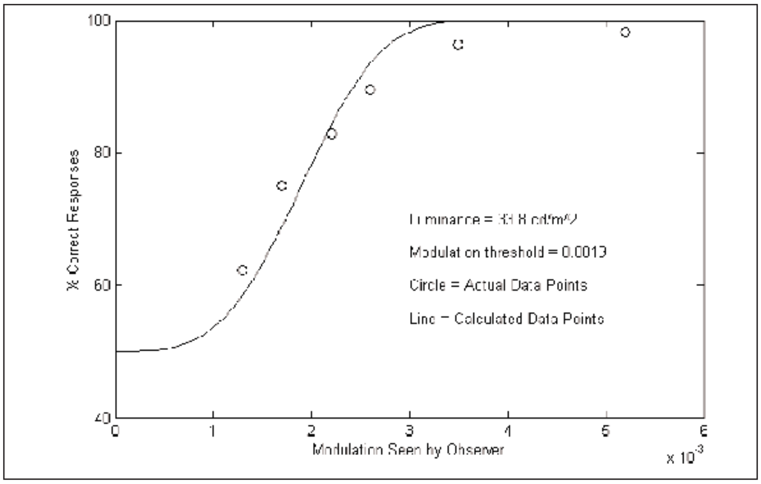

Figure 6. Determination of the modulation threshold for the 33.8 cd/m² luminance level.

observers were eliminated from the analysis, the number of observers' data used at each luminance level was 68 at the lowest luminance level, 75 at the middle luminance level, and 78 at the highest luminance level.

The interest here, is in determining how many observers are likely to see the contouring artifact given the DCDM bit-depth and encoding. This would justify eliminating from the analysis those observers who could not see the square waves at a modulation 3 to 4 bits less than the maximum number of bits tested. Because the observers were given a visual acuity test before the experiment and all showed a visual acuity of 20/30 or better (many were 20/15), it is apparent that the observers should have been able to see the square waves.

The observers were assigned seats in the theater; they were placed in four groups at distances of approximately 27, 41, 57, and 77 ft from the screen. These distances corresponded to 1.3, 2.0, 2.8, and 3.9 screen heights from the screen. Although there is some variation in the exact distance of any one individual in any group from the screen, those variations have no significant impact on the calculated visual modulation threshold as shown in Figs. 7, 8, and 9. In fact, the number of pixels in the square waves were selected so that the square waves were near the minimum in the visual modulation threshold vs. frequency curve. In this way, the experiment was designed so that the observer's distance from the screen had a minimal effect on the visual modulation threshold.

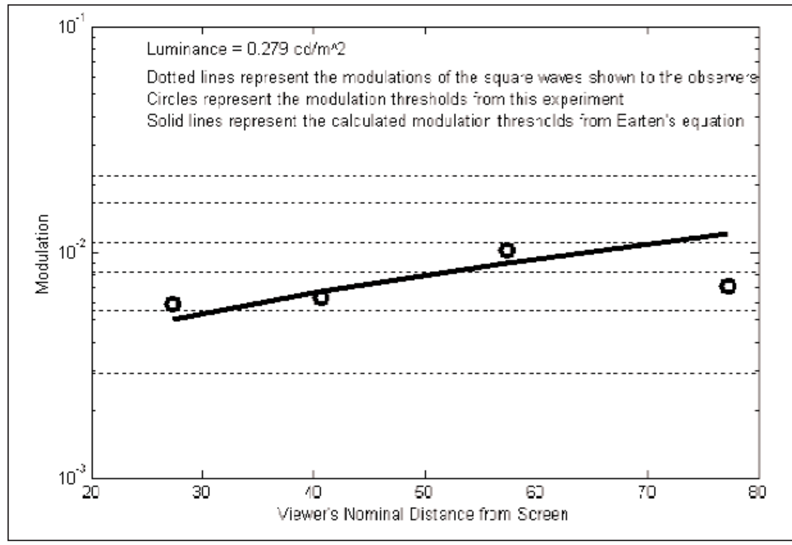

Figure 7. Modulation thresholds determined from this experiment and calculated from Equations 5 and 8 for the average luminance of 0.279 cd/m^2.

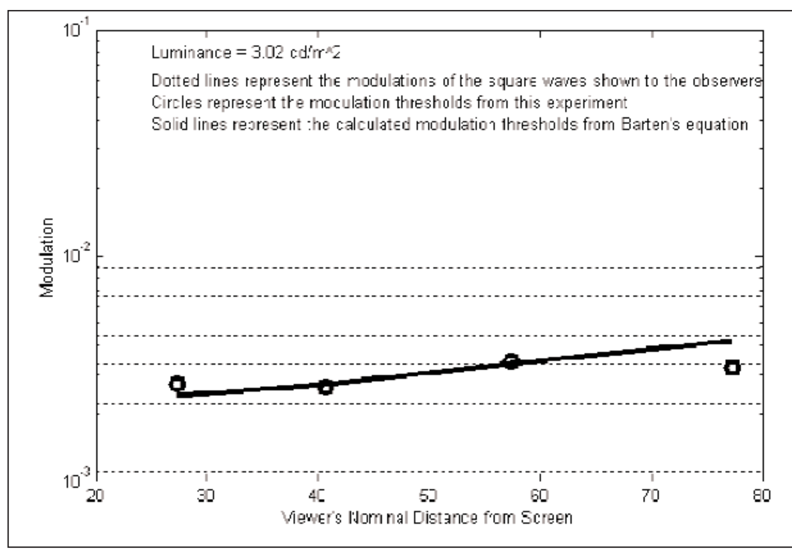

Figure 8. Modulation thresholds determined from this experiment and calculated from Equations 5 and 8 for the average luminance of 3.02 cd/m^2.

In Table 1, Group 1 was 27 ft from the screen, Group 2 was 41 ft from the screen, Group 3 was 57 ft from the screen, and Group 4 was 77 ft from the screen.

Because this is psychometric data, the points can be fit to a curve of the form

$$p2afc(m) = 1/2 + (1/2) * (1- \exp(-(m/\alpha)^{\beta})) \quad (16)$$

where p2afc(m) is the predicted fraction, correct responses for modulation m, and α and β are constants.

$$\alpha = m_o/(1n\ 2)^{(1/\beta)} \quad (17)$$

$$\beta = k/0.87 \quad (18)$$

where m_0 is the modulation, 75% of the responses are correct, and k is the k in Equation 8 and given by Barten to be 3.0. Although Barten varied k in order to better fit the experimental data, the value 3.0 is used in

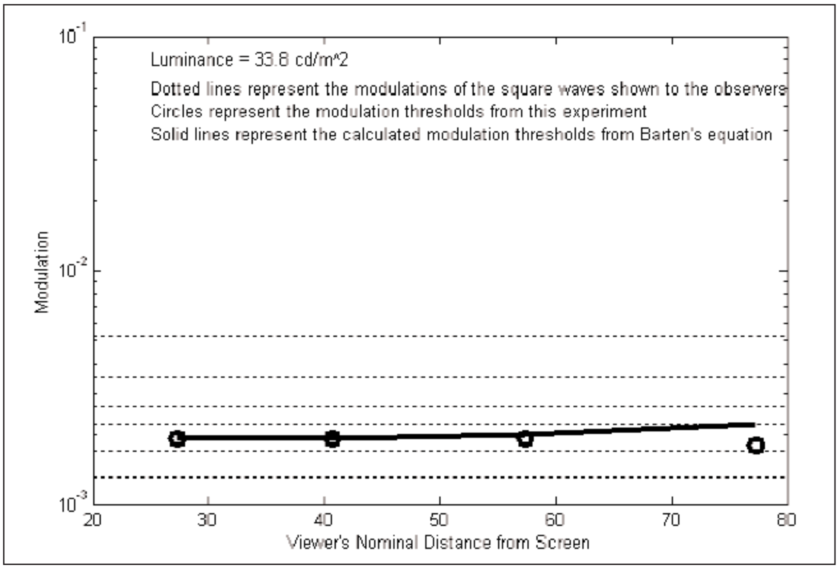

Figure 9. Modulation thresholds determined from this experiment and calculated from Equations 5 and 8 for the average luminance of 33.8 cd/m².

analyzing all of the data. m_0 is the threshold of modulation being sought. It is referred to as the 50% detection probability because at that point, 50% of the observers saw the square waves and responded correctly and 50% of the observers were guessing at the orientation. Of those 50% of the observers who were guessing, 50% (25% of the observers) guessed correctly and 50% guessed incorrectly. Therefore, 50% saw the square waves and responded correctly and 25% guessed correctly so that 75% of the responses were correct. The method of determining m_0 was one of varying m_0 over a wide range, calculating α from Equation 17, and calculating p2afc at the modulation values, m, that was used in the experiment. The best estimate of m_0 is the value that has the minimum sum of squares error between the measured fraction correct responses and the calculated p2afc values. Figures 4 through 6 show plots of the measured data and the p2afc values that give the minimum sum of squares error for each luminance level using the results from all of the observers independent of where they were sitting in the theater.

Similar calculations were done using the data from each of the individual groups of observers in Table 1. The minimum modulation thresholds calculated from data for each of the groups in the theater are shown in Table 2.

There are two other methods, probit analysis and logit analysis, which are commonly used to calculate visual thresholds from the observers' data like that gathered in this experiment.[2] These techniques are also used to analyze the data, but the results calculated thresholds that were the same as reported in Table 2. From both the probit analysis and the logit analysis, a confidence interval around the calculated threshold is easy to compute. The confidence intervals calculated were essentially the same in either case, so the probit confidence interval is shown in Table 2.

Figures 7 through 9 show that the agreement between the modulation thresholds determined in this experiment and from calculations using Equations 5 and 8 is excellent. Because the lowest four lines in these figures represent the modulation from square waves made from one-, two-, three-, and four-code value changes at each luminance level, the average of the observers in this experiment required either a two-

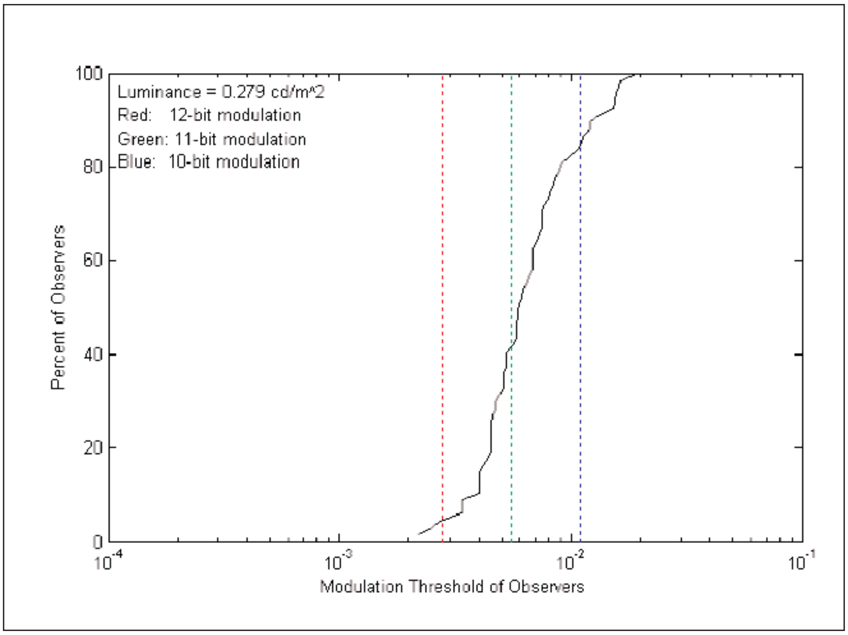

Figure 10. Cumulative Frequency Histogram of the modulation threshold for all of the observers at average luminance of 0.279 cd/m².

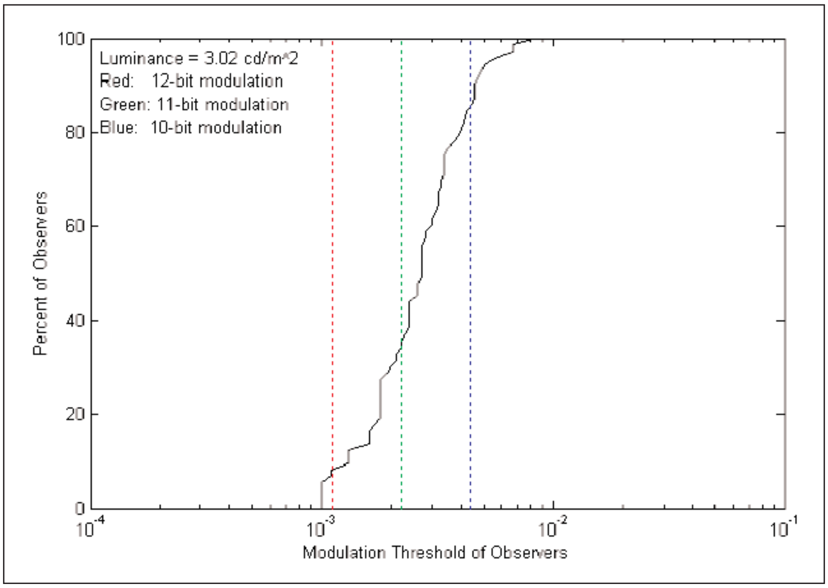

Figure 11. Cumulative Frequency Histogram of the modulation threshold for all of the observers at average luminance of 3.02 cd/m².

or a three-code value change in order to see the square waves. Because the judgments from the observers who could not see the highest modulation square waves have already been discarded from the analysis, these average results show the average modulation thresholds for the observers who are most sensitive to the luminance changes.

However, one concern is not whether the average of a group of people can see any digital artifacts, but how many of the people can see the artifacts. Therefore, the same calculations were performed to determine the modulation threshold of each of the observers at each of the luminance levels. Figures 10 through 12 show these results as cumulative frequency histograms. Also shown, are the minimum modulations that bit depths of 10-bit, 11-bit, and 12-bit encodings allow when an equation of the form shown in Equations 14 and 15 are used. At all luminance levels, a majority of the observers show a modulation threshold smaller than the modulation of a one-code value change with 10-bit encoding. However, only a very small number of observers show a modulation threshold smaller than the modulation of a one-code value change with 12-bit encoding.

Discussion and Conclusion

This experiment was designed to answer two questions: (1) Do the predictions of the Barten equation apply to the situation where images are digitally projected in a dark theater? and (2) What is the distribution of observers' visual modulation thresholds? Note that the experiment does not directly indicate the bit depth needed to avoid contouring in digitally projected images. However, this can be deduced from an analysis of the answers to the two questions.

Based on the results shown in Figs. 7 through 9, it can be concluded that the Barten equation predictions do apply to the digitally projected images in a dark theater. The differences in the predictions and the results are very small. The only region of consistent difference is the group of observers at the greatest distance from the screen. At all three average luminance levels, this group of observers shows a lower threshold than is predicted by the Barten equation. Because each observer gave responses from only one position in the theater, it cannot be concluded that the difference between the Barten equation prediction and the results from

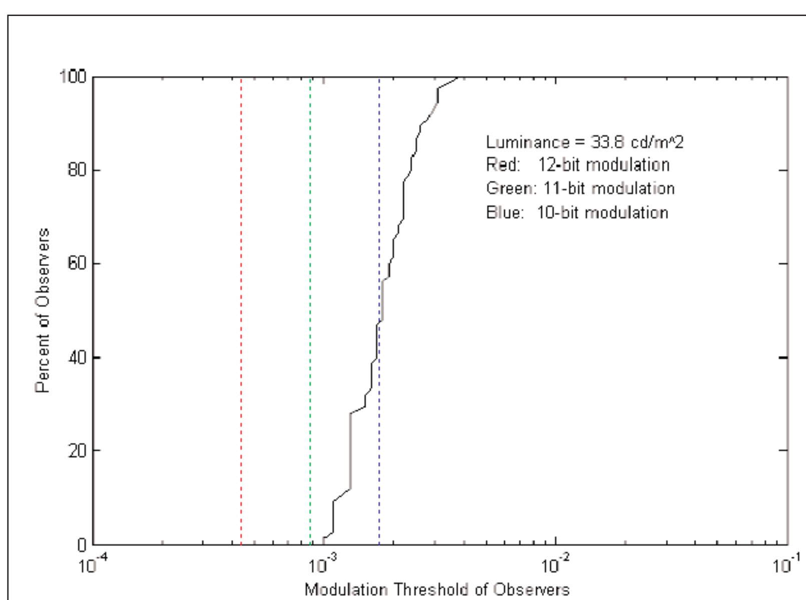

Figure 12. Cumulative Frequency Histogram of the modulation threshold for all of the observers at average luminance of 33.8 cd/m².

Table 3—Percentage of the Observers Whose Visual Modulation Threshold Fell at or Below the 10-bit, 11-bit, and 12-bit Encoding Modulation

Luminance cd/m^2	12-bit encoding	11-bit encoding	10-bit encoding
0.270	4.5%	40.3%	83.6%
3.02	8.2%	35.6%	84.9%
33.8	0%	0%	46.7%

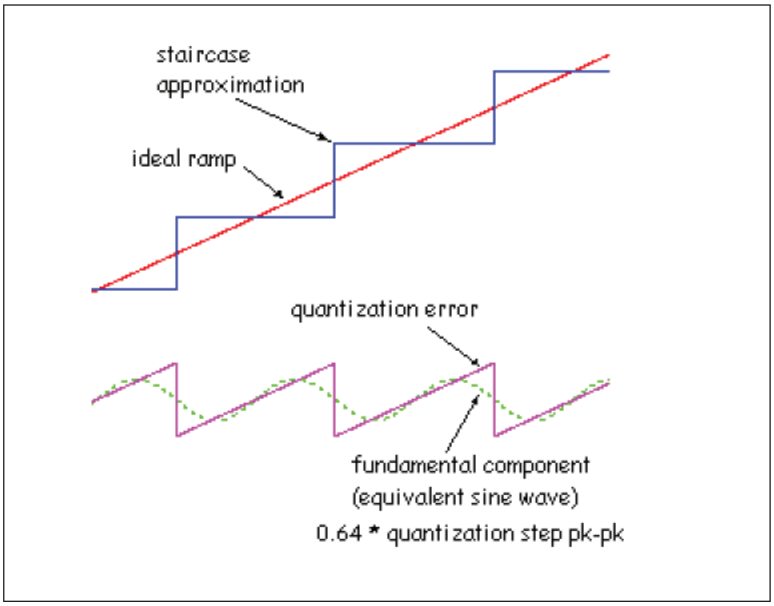

Figure 13. The staircase representation of a gradual ramp.

observers is due to the most sensitive observers sitting the farthest from the screen or if there is a real difference between the predictions and the measured results. In any case, the difference is small and not significant in terms of the question of the bit depth needed for encoding of the luminance in the DCDM, and the observed modulation at the farthest distance from the screen is the lowest visual modulation threshold only at the highest luminance tested. Therefore, the Barten equation can be confidently used for any predictions of the visual modulation threshold.

Because the Barten equation is based on fitting data from a variety of observers to one equation and the parameters k, η, and σ_0 were varied by Barten to fit any one set of experimental data, the Barten equation does not give an estimate of the distribution of visual modulation thresholds that a group of people would show. In this experiment, the results were discarded from those observers who by their observations indicated that they could not see the square waves. Therefore, the distribution of visual modulation thresholds was determined from the most sensitive observers. Table 3 shows the percentage of the observers, after discarding those who apparently could not see any of the square waves, but could see a 10-bit, 11-bit, and 12-bit encoding at each of the luminance levels. Based on these results, few observers will see a one-code value change with 12-bit encoding.

Although this experiment demonstrates that the minimum one-code value change that cannot be seen is a bit depth of 12 bits, the digital projectors in use today are being fed an 8-bit signal, compressed at 4:2:0. Because of the nature of the encoding equation, Equation 14, the modulation encoded by a one-code value change when the bit depth decreases by 1 bit, changes by a factor of 2. This can be seen in Fig. 2, where 10-bit and 12-bit encoding equations are compared. The modulation changes as the luminance changes, but the ratio of the modulation of the 10-bit encoding to the modulation of the 12-bit encoding is a constant 4.0 due to the fact that the encoding changed by 2 bits. So one can ask how, if 12-bit encoding is needed to encode luminance changes below the threshold of visibility, images encoded in 8 bits can perform acceptably today. This is a change in modulation by a factor of 16, because the change in bit depth is 4 bits.

In practical images, the contouring artifact occurs not when the image is 13 square waves, but when the image contains a low-contrast gradient in luminance. A gradient can be described by a region encoded by a code value of cv, then an adjacent region encoded by a code value cv+1, etc. This pattern provides one-half the modulation depth of the square wave case because the luminance continuously increases and returns neither to the average luminance nor to the lowest luminance as shown in Fig. 13.

Because the modulation threshold will also be increased by any noise, dithering, or grain in the image, it is possible to see how the 8-bit current images can be seen as displaying no contouring arti-

facts. This, then, raises the question whether 12-bit encoding is really needed to avoid the contouring artifact. Because there is definitely a cost involved in using more bits, there is a strong desire by the manufacturers of digital projection equipment to use the minimum number of bits needed to avoid artifacts. Twelve-bits may be the limit to what the visual system can see under ideal conditions including the ideal image (13 cycles of square waves), but that ideal image is contrived and does not represent a typical artifact.

Next Step

In order to test the entire proposed DCDM encoding algorithm, DCI worked with the American Society of Cinematographers (ASC) to photograph a series of scenes around the theme of a wedding to create the Standard Evaluation Material (StEM). The StEM images were captured with a variety of film types, film formats, and lighting conditions. This film was scanned, graded, and assembled to produce a short test film. This StEM short film will be used to practically validate the DCDM color encoding process, and DCI will make it available for proponents in the industry to use as test material.

Acknowledgments

The authors would like to acknowledge the contributions of the other members of the SMPTE Color ad hoc group: Jim Houston, George Joblove, Howard Lukk, Arjun Ramamurthy, Jeremy Selan, Kaz Tsujikawa, and Ron Williams.

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Appendix A

Method of Achieving 12-bit Modulation

There were two fundamental challenges in designing the experiment. Modulation was required to accurately emulate a 12-bit gamma 1/2.6 encoded system to provide the appropriate modulations on screen. For practical reasons, the experiment needed to be scripted so it would present the patterns in a predetermined order, at fixed time intervals.

At the time of developing the experiment, practical 12-bit sources were not readily available. Instead, capabilities within the projector were used to achieve these two require-

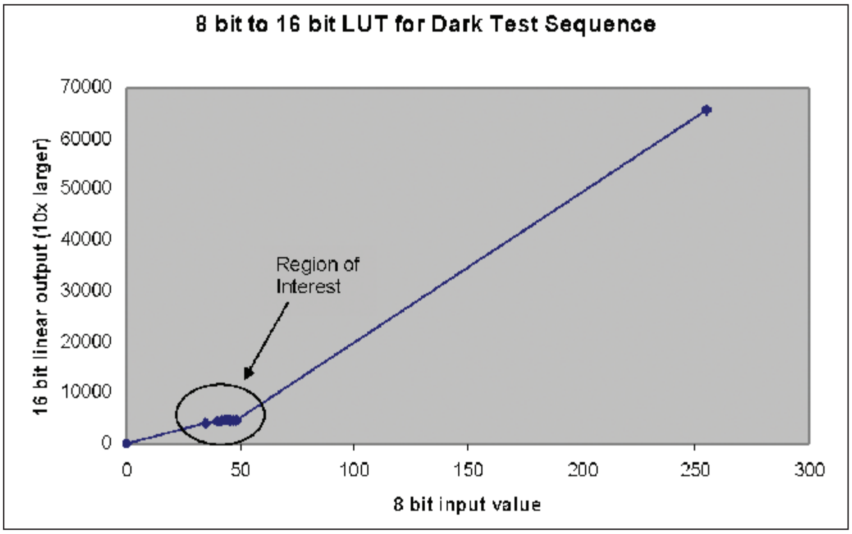

Figure 14. Plot of LUT values used for dark sequence. Note that 8-bit input value maps to high precision 16-bit output. Also note that the luminance value chosen for the mapping is ten times desired for the experiment, so is attenuated using a neutral density filter.

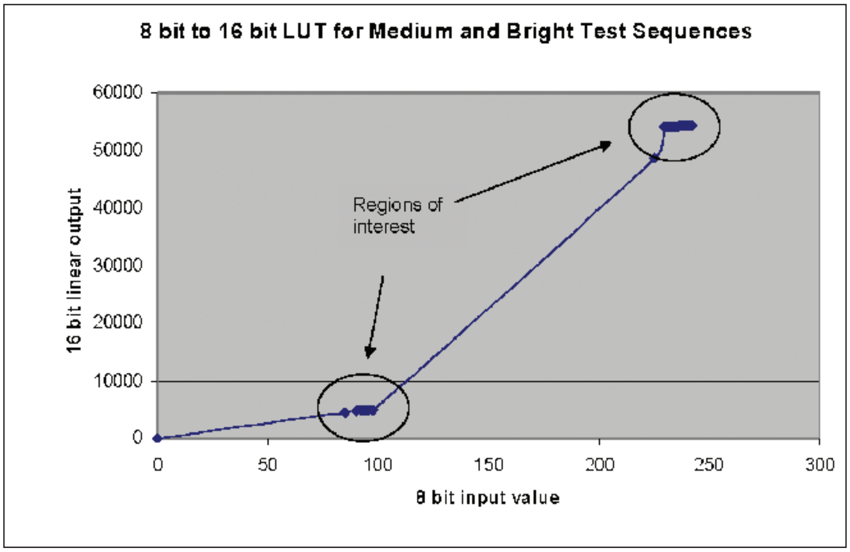

Figure 15. Plot of LUT values used for medium and bright sequences. Note that 8-bit input value maps to high-precision 16-bit output.

ments. The TI DLP Cinema projector drives its micromirror modulators in a 16-bit linear mode. The modulation is achieved through rapidly switching the mirror on and off during the frame time. The on and off cycle is very accurately modeled by the operating software within the projector. Accurate modulation levels can be achieved by addressing specific 16-bit values for mirror luminance.

The DLP Cinema projector also contains dual 8-bit graphics overlay buffers, which will display stored patterns. These buffers are managed through XML scripting.

The experiment was developed to address three brightness regions of interest 33.8, 3.02, and 0.279 cd/m^2 (Table 1). For these experiments, maximum (full on) white for the projector is 41 cd/m^2. The test pattern values were derived as follows:

- The luminance in cd/m^2 was calculated to correspond to a 12-bit gamma coded input, with the desired modulation levels.
- The luminance levels were converted to 16-bit linear code values that the projector uses to drive the micromirror modulators.
- Eight-bit numbers were selected to represent the desired luminance levels and mapped to the 16-bit luminance codes. This mapping was coded in a look-up table (LUT) and loaded into the projector (Figs. 14 and 15).

For the lowest luminance region of interest, it was felt that the 16-bit linear modulation was not sufficiently precise, so luminance values were calculated that corresponded to 10 times the required luminance, and a 1.0 ND filter was placed in front of the projector to achieve the correct levels.

Patterns were developed using the 8-bit values that mapped into the desired luminance. These were saved as Targa files and loaded into the projector. An XML script was written that loaded each test pattern in a pre-determined order and managed the time the pattern was on the screen. Each luminance level had its own XML script.

To run the experiment, the appropriate XML file was selected and run.

A contribution received April 2004.

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Matthew Cowan has over 20 years experience in the development and application of new products in the media and display fields. His comprehensive background includes development of electronic projection systems, design of complex mastering and distribution systems, strategic technology sourcing, reviews of advanced electronic display products, and detailed analysis of compression schemes for digital images.

Cowan was instrumental in developing the current mastering processes used in digital cinema, which introduced the use of the mastering theater for color and dynamic range adjustment. He has been an invited speaker and panelist for numerous industry conferences and film festivals. He chaired the SMPTE DC28.3 study group on compression for digital cinema and remains an active DC28.0 participant.

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