NISTIR 6792

Characterization of Projection Systems for the MPEG-4 Digital Cinema Compression Scheme Evaluation

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Dr. Karen H. Brown, Acting Director

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1. Background

The international standards organization officially titled ISO/IEC/JTC1/SC29/WG11, otherwise known as the Moving Picture Experts Group (MPEG), and the Digital Cinema Ad Hoc Group under MPEG, subjectively assessing various compression algorithms for digital cinema applications. The group designed an experiment involving two digital cinema projectors: a projector using a digital micromirror device (DMD), and a cathode ray tube (CRT) projector. Various trained observers viewed sequential and side-by-side digital cinema clips (one side compressed, the other uncompressed) and rated the quality of the images for each projector. These tests were held at the Entertainment Technology Center (ETC, Hollywood, CA), located in the historic Warner/Pacific Theater on Hollywood Boulevard.

The MPEG Digital Cinema Ad Hoc Group was concerned about whether the system being used (server, interface, projector, screen, viewing room) would block out important details in the assessment of the compression algorithms. NIST was asked to oversee initial measurements made of projectors in order to characterize their performance before the subjective visual testing was begun. THX (a division of LucasFilm, Burbank, CA) made the actual measurements. The responsibilities were broken down as follows:

NIST's role—to oversee the measurement process:

- perform diagnostics to determine instrumentation limitations and provide solutions when possible;
- determine stray-light contributions of the room;
- determine other factors that might influence the measurements;
- provide an uncertainty assessment of the measurement process;
- assure that procedures, whenever possible, follow the relevant ANSI and VESA standards;
- provide a spreadsheet for data collection and analysis;
- and provide the MPEG Digital Cinema Ad Hoc Group with test patterns.

THX's role:

- provide measurement equipment;
- perform actual measurements used to evaluate the projectors;
- and provide expertise as needed.

The following describes the results of the projector characterization as reported to the MPEG Digital Cinema Ad Hoc Group in July 2001.

2. Characterization of Projection Systems for the MPEG-4 Digital Cinema Compression Scheme Evaluation

The following data was collected by the THX Division of LucasFilm Ltd., Burbank, CA and by Paul Miller of the Entertainment Technology Center on June 21, 2001. The relative expanded uncertainty of the photometric measurements (with a coverage factor of k=2) was 12 % in luminance, and ±0.005 in 1931 CIE chromaticity coordinates, based on the measurements made by THX. NIST provided technical expertise, measurement diagnostics, test patterns, and uncertainty assessment. NIST also ensured that, where relevant, each measurement followed the appropriate procedures described in the following standards [1]:

ANSI/NAPM IT7.228-1997 Electronic Projection—Fixed Resolution Projectors
ANSI/PIMA IT7.227-1998 Electronic Projection—Variable Resolution Projectors
VESA Flat Panel Display Measurements Standard Version 2.0 (June 2001)

These measurements characterize the projector system performance on June 21, 2001, at the Warner/Pacific Theater and at the particular settings and configurations on that day. The projection system includes the combined effect of the digital cinema projectors, projection screen, storage system, interfaces, and converters.

The assigned uncertainty does not incorporate shifts due to drift, environmental changes, or readjustment of the projectors. Neither does the uncertainty imply a calibration or certification by NIST. Traceability to NIST can be inferred through the calibration of the measurement equipment provided by THX, but not through any direct comparison with NIST equipment as used at the site.

The measurements and procedures were established through discussions by NIST with Ad Hoc Group members (see Table 3). Some of these measurements and procedures were not performed due to time constraints imposed by the Digital Cinema Ad Hoc Group. In addition to the set-up and diagnostic measurements, the following measurements were made:

Room configuration (geometry of projector, viewer, and screen)
Room conditions (ambient light)
Screen gain
Light output and nonuniformity of white and black
Color temperature and white point
Color chromaticity of primaries and color gamut area
Contrast ratio (checkerboard, sampled, and full-screen)
Gray-scale levels and gamma estimation
Resolution and contrast modulation
Aspect ratio

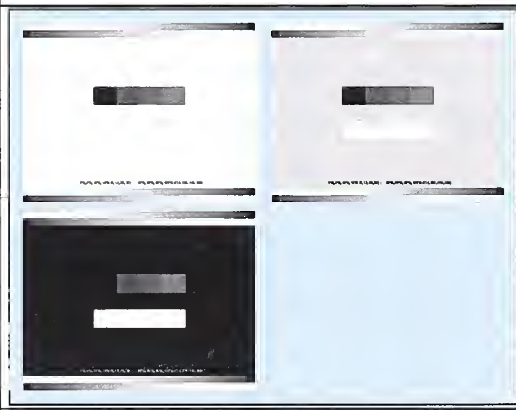
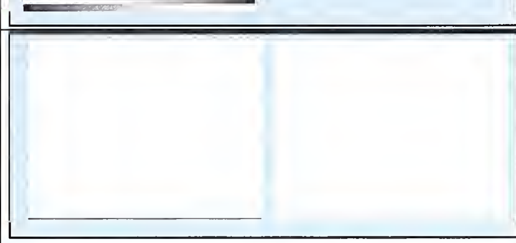
Patterns were chosen based upon the list of requested measurements and drawn from the set of test patterns developed by Kelley at NIST and Miseli at Sun Microsystems [2]. Descriptions of the patterns described in Table 2 may be found in either the VESA FPDM or the ANSI/PIMA electronic projection standards. Electronic copies of the image files used, in the proper formats,

are available at http://www.itl.nist.gov/div895/TestPatterns/index.html. Because the two display interfaces and image formats differ, the test patterns were generated in the same formats and stored and displayed using the same system components employed for the subjective viewing tests. Pattern generation was based on specifications in the relevant SMPTE standard [3]. The digital formats for the test patterns and cinema clips for the two projectors are as described in the following table.

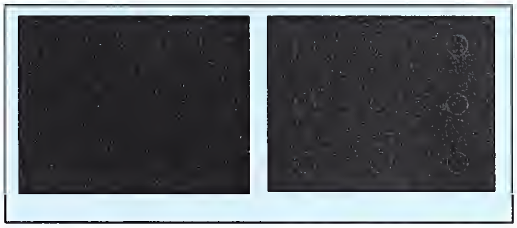
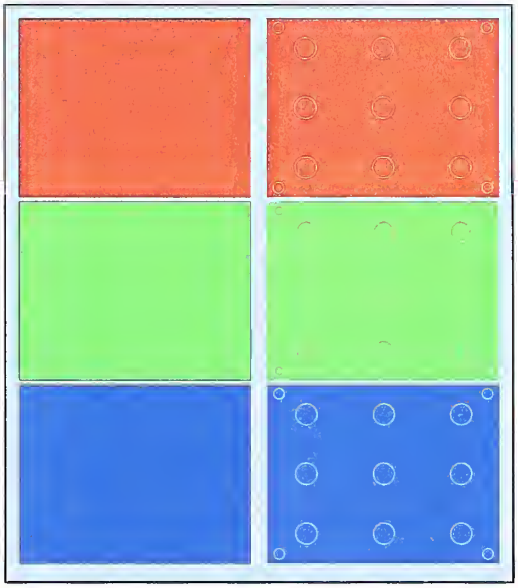
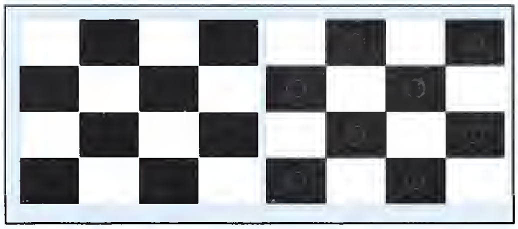
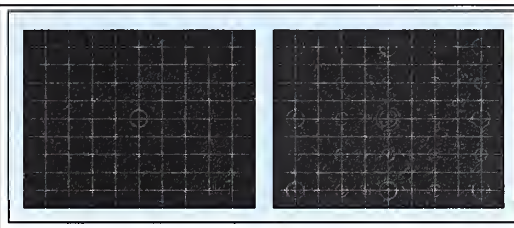
Table 1. Image Formats for Projection Systems

Image Attribute	DMD Projection System	CRT Projection System
Color-coding components [4]	R'G'B'	$Y'C'_BC'_R$
Addressable active pixels per frame	1280 X 1024	1920 X 1080
Addressable stored pixels per frame	1920 X 1080	1920 X 1080
Sampling	4:4:4	4:2:2
Bits per sample	10	10
Full range Rec. 709 code values*	[64, 940] for R, G, and B	[64, 940] for Y [64, 960] C_B, and C_R
Image file format	DPX [5]	YUV

Table 2. Test Patterns

DESCRIPTION	PATTERN
SETUP PATTERNS Used in setup of projector. White background version is based upon ANSI setup pattern	
FULL SCREEN WHITE Used for white luminance, white nonuniformity, color temperature, and full-screen contrast measurements.	

* These code values map to the full range of light output of both projectors. See Ref. 4, p. 12.

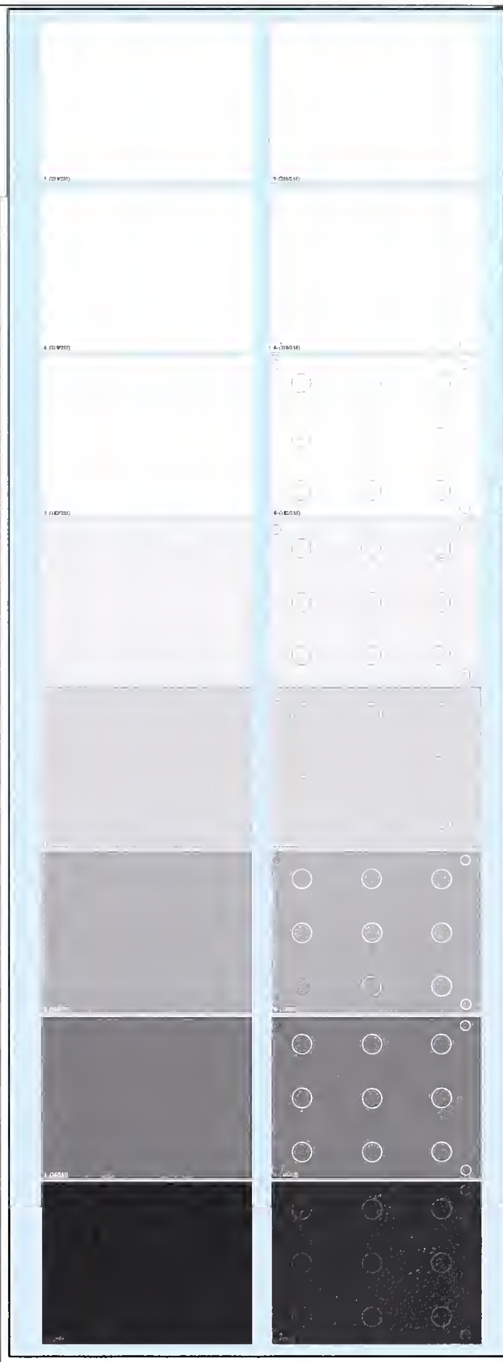
FULL SCREEN BLACK Used for black luminance, black nonuniformity, and full-screen contrast measurements.	
FULL SCREEN COLOR PRIMARIES Used for color luminance and chromaticity measurements.	
4×4 CHECKERBOARD CONTRAST PATTERN Used for checkerboard contrast (ANSI contrast)	
ALIGNMENT PATTERNS Used for aspect ratio measurements	

FULL SCREEN GRAY LEVELS

Used for gray-level luminance and chromaticity measurements, and gamma estimation.

Eight full-screen gray levels were used, assuming 10 bits, with Rec.709 range [64 – 940]:

Black (0) = 64/940
Level (1) = 189/940
Level (2) = 314/940
Level (3) = 439/940
Level (4) = 564/940
Level (5) = 689/940
Level (6) = 815/940
White (7) = 940/940



N×N HORIZONTAL AND VERTICAL GRILL PATTERNS (1×1, 2×2, 3×3, 4×4, 5×5)

Used for contrast modulation and resolution measurements. Unless specified otherwise, these patterns will always start with white at left or top. Not all grill patterns are shown here. Patterns shown are magnified for demonstration purposes.

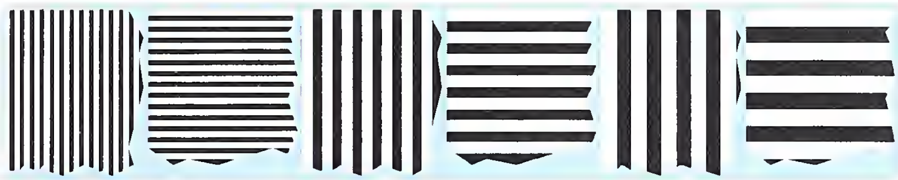


Table 3. Test Procedures

1) Projector setup

a) references

ANSI/NAPM IT7.228 (IEC Draft 61947-1)

1.1 Stipulations

ANSI/NAPM IT7.227 (IEC 61947-2)

1.2 Stipulations

VESA FPDM Ver 2.0 (2001)

301 Setup of Display and Equipment

b) patterns

- i) Setup pattern with white background
- ii) Setup pattern with 50 % gray background
- iii) Setup pattern with black background
- iv) Full-screen white field pattern
- v) Others as needed

c) procedures

- i) Place full-screen white field on screen.
- ii) Warm up projector for a minimum of 20 min.
- iii) Adjust projector controls to desired settings using setup patterns and other appropriate patterns (performed by projector manufacturers).
- iv) At this point, projector controls remain unchanged throughout measurements for the results to be valid.

2) Evaluate measurement apparatus and room conditions

a) references [6]

VESA FPDM Ver 2.0 (2001)

301-2 Measurement and Display Conditions

301-3 Display Setup and Subjective Testing

301-4 Measurement Repeatability (Luminance)

A101 Veiling Glare and Lens Flare Errors

A221 Statements of Uncertainty

b) patterns

i) Full-screen white field pattern

ii) Full-screen 4 × 4 checkerboard pattern

c) procedures [6]

i) Evaluate alignment error of illuminance meter.

ii) Determine illuminance position error.

iii) Determine repeatability of luminance measurements.

iv) Measure ambient light conditions.

v) Determine veiling glare effects.

vi) Determine other stray-light contributions.

vii) Measure screen gain.

3) Light output, color, and nonuniformity of white and black

a) references

ANSI/NAPM IT7.228 (IEC Draft 61947-1)

4 Light output measurement and specification

4.2 Light uniformity

ANSI/NAPM IT7.227 (IEC 61947-2)

4.1 Light output measurements

5.1 Light output specifications

5.2 Light output uniformity

VESA FPDM Ver 2.0 (2001)

306-1 Sampled Uniformity & Color of White

306-2 Sampled Uniformity of Black

b) patterns

i) Full-screen white field pattern

ii) Full-screen white field pattern with 13 measurement alignment circles

iii) Full-screen black field pattern

iv) Full-screen black field pattern with 13 measurement alignment circles

c) procedures

i) Place white field pattern onto projection screen. Use the pattern with 13 measurement alignment circles to align LMD at each measurement point, and switch to pattern without circles for measurement.

ii) Place LMD at design viewing location.
iii) Measure luminance at each measurement location, L_i, where i= 1,…,13.
iv) Calculate the sampled white luminance $L_w = \frac{1}{n}\sum_{i=1}^{n=9} L_i$ and the sampled chromaticity $x_w = \frac{1}{n}\sum_{i=1}^{n=9} x_i$, $y_w = \frac{1}{n}\sum_{i=1}^{n=9} y_i$ for the n=9 positions on the white field (don't use the four corner positions).
v) Calculate the nonuniformity of white, $Nonuniformity = 100\%\left(1 - \frac{L_{min}}{L_{max}}\right)$, where L_{max} and L_{min} are the maximum and minimum measured white luminance, respectively, of the sampled white luminance set: L_i, where i = 1,…, 13.
vi) Place black field pattern onto projection screen. Use the pattern with 13 measurement alignment circles to align LMD at each measurement point, and switch to pattern without circles for measurement.
vii) Place LMD at design viewing location.
viii) Measure luminance at each measurement location, L_i, where i= 1,…,13.
ix) Calculate the sampled black luminance $L_b = \frac{1}{n}\sum_{i=1}^{n=9} L_i$ and the sampled chromaticity $x_b = \frac{1}{n}\sum_{i=1}^{n=9} x_i$, $y_b = \frac{1}{n}\sum_{i=1}^{n=9} y_i$ for the n=9 positions on the black field (don't use the four corner positions).
x) Calculate the nonuniformity of black, $Nonuniformity = 100\%\left(1 - \frac{L_{min}}{L_{max}}\right)$, where L_{max} and L_{min} are the maximum and minimum measured black luminance, respectively, of the sampled black luminance set: L_i, where i = 1,…, 13.
xi) Report luminance, nonuniformity, and chromaticity of white and black.

4) Color temperature and white point

a) references:
ANSI/NAPM IT7.228 (IEC Draft 61947-1)
5.5 Color measurements
ANSI/NAPM IT7.227 (IEC 61947-2)
6.6 Color measurements
VESA FPDM Ver 2.0 (2001)
302-1 Luminance and Color of Full-Screen White

b) patterns:
i) Full-screen white field
ii) Full-screen white field with 13 measurement alignment circles

c) procedures:
i) Place white field pattern onto projection screen. Use the pattern with 13 measurement alignment circles to align LMD at each measurement point, and switch to pattern without circles for measurement.

ii) Direct LMD at center screen position from design viewing location.

iii) Measure the white-point chromaticity (x_W, y_W) and the CCT.

iv) Use formulas 5(3.3.4) and 6(3.3.4) in Wyszecki and Stiles, *Color Science* (pp. 145-146, second Ed., Wiley, 1982) to compute the point (x_d, y_d) on the daylight locus that is associated with CCT T_B. First, define g = 1000 / T_B

If $T_B < 7000$, then $x_d = -4.6070\, g^3 + 2.9678\, g^2 + 0.09911\, g + 0.244063$.
If $T_B > 7000$, then $x_d = -2.0064\, g^3 + 1.9018\, g^2 + 0.24748\, g + 0.237040$.
In either case, $y_d = 3.000\, x_d^2 + 2.870\, x_d - 0.275$.

v) Convert (x_W, y_W) and (x_d, y_d) to $u'v'$ coordinates:

$(u'_W, v'_W) = (4\, x_W, 9\, y_W)/(3 + 12\, y_W - 2\, x_W)$
$(u'_d, v'_d) = (4\, x_d, 9\, y_d)/(3 + 12\, y_d - 2\, x_d)$

vi) Evaluate $\Delta u'v'$ between (u'_W, v'_W) and (u'_d, v'_d):

$$\Delta u'v' = \sqrt{(u'_W - u'_d)^2 + (v'_W - v'_d)^2}$$

vii) Report CCT, chromaticity of white point, and color difference.

5) Color chromaticity and gamut area

a) references:

ANSI/NAPM IT7.228 (IEC Draft 61947-1)
5.51 Color chromatically
5.52 Color uniformity
ANSI/NAPM IT7.227 (IEC 61947-2)
6.6.1 Color chromaticity
6.6.2 Color uniformity
VESA FPDM Ver 2.0 (2001)
302-4 Gamut and Color of Full Screen
302-4A Gamut-Area Metric

b) patterns:

i) Full-screen red field
ii) Full-screen red field with 13 measurement alignment circles
iii) Full-screen green field
iv) Full-screen green field with 13 measurement alignment circles
v) Full-screen blue field
vi) Full-screen blue field with 13 measurement alignment circles

c) procedures:

i) For each full-screen primary (RGB), place the appropriate pattern onto projection screen. Use the pattern with 13 measurement alignment circles to align LMD at the measurement point, and switch to pattern without circles for measurement.
ii) Measure luminance and chromaticity at center screen for all of the full-screen primaries.

iii) Calculate projector gamut as a percentage of color space using center-screen values: $A = 256.9\left|(u'_r - u'_b)(v'_g - v'_b) - (u'_g - u'_b)(v'_r - v'_b)\right|$.

iv) Report color gamut area, and for each primary color, report center screen luminance and chromaticity.

6) Contrast ratio

a) references:

ANSI/NAPM IT7.228 (IEC Draft 61947-1)
 4.3 Contrast ratio
ANSI/NAPM IT7.227 (IEC 61947-2)
 5.3 Contrast ratio
VESA FPDM Ver 2.0 (2001)
 302-3 Darkroom Contrast Ratio of Full Screen
 306-3 Sampled Uniformity of Contrast Ratio
 304-9 Checkerboard Luminance and Contrast (n×m)

b) patterns:

i) Full-screen white field
ii) Full-screen white field with 13 measurement alignment circles
iii) Full-screen black field
iv) Full-screen black field with 13 measurement alignment circles
v) Full-screen 4 × 4 checkerboard pattern
vi) Full-screen 4 × 4 checkerboard pattern with 16 measurement alignment circles

c) procedures:

i) Using the center-screen white and center-screen black luminance measurements, calculate full-screen contrast ratio $C = \frac{L_w}{L_b}$.

ii) Using the sampled white and sampled black luminance measurements, calculate average sampled contrast ratio $C_{Uave} = \frac{1}{n}\sum_{i=1}^{n=9} \frac{L_w}{L_b}$ where i=1,...,9 sampled points on the screen.

iii) Calculate nonuniformity of contrast ratio $= 100\%\left(1 - \frac{C_{min}}{C_{max}}\right)$, where C_{max} and C_{min} are the maximum and minimum contrast, respectively, of the sampled contrast set: C_i, where $i = 1,\ldots,13$.

iv) Place 4×4 checkerboard projection screen. Use the pattern with 16 measurement alignment circles to align LMD at each measurement point, and switch to pattern without circles for measurement.

v) Direct LMD at center screen position from design viewing location.

vi) Measure the screen luminance at each of the 16 points, compensating for veiling glare as necessary.

vii) Calculate the average checkerboard contrast $C_{Cave} = \frac{1}{n}\sum_{i=1}^{n}\frac{L_w}{L_b}$, where n=8 (number of black and white checkerboard pairs).

viii) Report the full screen contrast, average sampled contrast, checkerboard (ANSI) contrast, and contrast nonuniformity.

7) **Gray Scale**

a) references:
VESA FPDM Ver 2.0 (2001)
302-5 Gray Scale of Full Screen
302-5a Determination of "Gamma"

b) patterns (full-screen gray levels w/ center measurement alignment circles with Rec.709 range [64 – 940]):
   i) Full-screen black (0) = 64
   ii) Full-screen black (0) = 64 with measurement alignment circles
   iii) Full-screen gray level (1) =189
   iv) Full-screen gray level (1) =189 gray with measurement alignment circles
   v) Full-screen level gray (2) = 314
   vi) Full-screen level gray (2) = 314 with measurement alignment circles
   vii) Full-screen level gray (3) = 439
   viii) Full-screen level gray (3) = 439 with measurement alignment circles
   ix) Full-screen level gray (4) = 564
   x) Full-screen level gray (4) = 564 with measurement alignment circles
   xi) Full-screen level gray (5) = 689
   xii) Full-screen level gray (5) = 689 gray with measurement alignment circles
   xiii) Full-screen level gray (6) = 815
   xiv) Full-screen level gray (6) = 815 gray with measurement alignment circles
   xv) Full-screen white (7) = 940
   xvi) Full-screen white (7) = 940 with measurement alignment circles

c) procedures:
   i) For each full-screen gray level, place the appropriate pattern onto projection screen. Use the pattern with 13 measurement alignment circles to align LMD at the measurement point, and switch to pattern without circles for measurement.
   ii) Direct the LMD at center screen from the design viewing location.
   iii) Measure center screen luminance *L* and chromaticity (*x*,*y*) for the full-screen gray scale levels.
   iv) Plot the electro-optic transfer function and estimate gamma. Because the full dynamic gray scale has black level code of 64, the gray scale codes are adjusted by subtracting 64 for the gamma estimate. Determine the gamma by fitting a curve to the luminance data using the model: $L = aV^{\gamma} + L_b$, or in terms of logs, $\log(L - L_b) = \gamma\log(V) + \log(a)$, where a and γ relate the signal level V to the luminance L and L_b is the black-level luminance.

v) Report gray scale luminances and chromaticity, gamma estimate, and show plot of electro-optic transfer function.

8) Resolution

a) references:
ANSI/NAPM IT7.228 (IEC Draft 61947-1)
4.4 Small area contrast ratio for alternating black and white pixels
5.1 Displayable format (ANSI Resolution)
ANSI/NAPM IT7.227 (IEC 61947-2)
6.1 Variable resolution measurement and specification
Annex G Alternative method for measuring resolution using the NIDL grille contrast method
VESA FPDM Ver 2.0 (2001)
303-2 N×N Grille Luminance and Contrast
303-7 Resolution from Contrast Modulation

b) patterns (black on white):
i) 1×1 vertical grill (1 column on, 1 column off)
ii) 2×2 vertical grill
iii) 3×3 vertical grill
iv) 4×4 vertical grill
v) 5×5 vertical grill
vi) 1×1 horizontal grill (1 row on, 1 row off)
vii) 2×2 horizontal grill
viii) 3×3 horizontal grill
ix) 4×4 horizontal grill
x) 4×4 horizontal grill

c) procedures:
i) Place the appropriate pattern onto projection screen.
ii) Direct the LMD at center screen from the design viewing position.
iii) Measure the black illuminance E_k and white illuminance E_w for several grilles and take the average for black and white.
iv) Calculate the contrast modulation $C_m = \frac{E_{peak} - E_{valley}}{E_w + E_k}$ for each pattern, where E_w and E_k are the average white and black checkerboard illuminances, respectively.

v) Calculate n_r, the calculated grille line width (in pixels) for which C_m is estimated to be equal to the contrast modulation threshold $C_T = 33\%$ (ANSI) or $C_T = 25\%$ (VESA):

$$n_r = n + \frac{C_T - C_m(n)}{C_m(n+1) - C_m(n)} \quad for\ C_m(n) < C_T < C_m(n+1).$$

vi) Calculate the resolution (in number of resolvable pixels) = $\frac{\#of\ addressable\ lines}{n_r}$ for both horizontal and vertical directions.

vii) Report addressability, resolution, and show contrast modulation plots.

9) Aspect Ratio

a) references:
ANSI/NAPM IT7.228 (IEC Draft 61947-1)
5.2 Aspect Ratio
VESA FPDM Ver 2.0 (2001)
501-2 Aspect Ratio

b) pattern:
i) Distortion pattern

c) procedures:
i) Place distortion pattern on screen.
ii) Measure horizontal distance across center, H.
iii) Measure vertical distance across center, V.
iv) Calculate aspect ratio $\alpha = \frac{H}{V}$.
v) Convert decimal aspect ratio to the nearest integer aspect ratio.

Table 4. PROJECTION SYSTEM[†] CHARACTERISTICS FOR MPEG DIGITAL CINEMA TESTING[‡]

DATE: June 21, 2001
LOCATION: Warner/Pacific Theater, Hollywood, CA
MEASUREMENTS TAKEN BY: Simon Allen, THX; Paul Miller, ETC
OBSERVERS Paul Boynton, Electronics and Electrical Engineering Laboratory, NIST
Charles Fenimore, Information Technology Laboratory, NIST

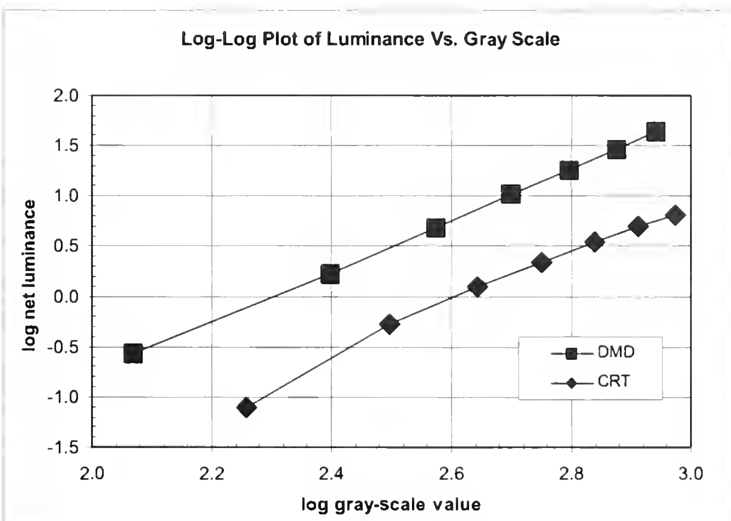
GEOMETRY		**DMD Projection System**	**CRT Projection System**
	Projeetor distance from eenter sereen	14 m	9 m
	Design viewing distanee from eenter sereen	5 m	5 m
	Angle of ineidence	0.4 °	10 °
	Angle of refleetanee	25 °	25 °
AMBIENT LIGHT (center screen, projector off)		0.02 lx	0.02 lx
SCREEN GAIN (from design viewing location)		1.0	1.0
LUMINANCE AND UNIFORMITY			
	Sampled luminanee of white	43 ed/m^2	4.6 ed/m^2
	Sampled luminanee of blaek	0.05 ed/m^2	0.01 ed/m^2
	Nonuniformity of white	32 %	59 %
	Nonuniformity of blaek	54 %	5.9 %
	Sampled eolor temperature	5837 K	6508 K
	Sampled white point (x,y)	(0.324, 0.362)	(0.313, 0.314)
LUMINANCE AND CHROMATICITY OF PRIMARIES			
	Luminanee of red	7.0 ed/m^2	2.7 ed/m^2
	Chromatieity of red (x,y)	(0.660, 0.305)	(0.659, 0.338)
	Luminance of green	18 ed/m^2	4.7 ed/m^2
	Chromatieity of green (x,y)	(0.251, 0.665)	(0.325, 0.590)
	Luminance of blue	3.1 ed/m^2	0.6 ed/m^2
	Chromaticity of blue (x,y)	(0.138, 0.070)	(0.146, 0.064)
	Color gamut area	39.5 %	32.6 %
CONTRAST			
	Full screen contrast ratio at eenter	880:1	940:1
	Sampled eontrast ratio (9-point)	930:1	690:1
	Contrast nonuniformity (13-point)	56 %	40 %
	Cheekerboard eontrast (4×4)	140:1	76:1

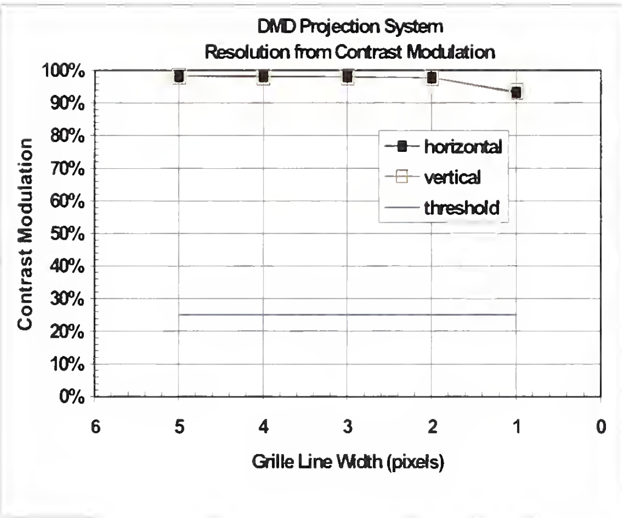
[†] Includes projector, screen, storage system, interfaces, and converters for luminance measurements. Illuminance measurements (including the resolution measurements) do not include the screen in the system.

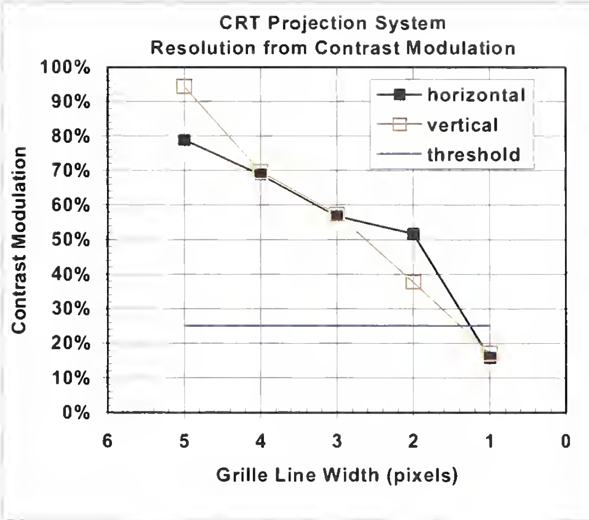
[‡] The relative expanded uncertainty for the photometric measurements is estimated to be ±12 % for a coverage factor of k=2, and for the colorimetric measurements, ±0.005 in CIE 1931 chromaticity coordinates (x ,y).

RESOLUTION		DMD Projection System	CRT Projection System
	Contrast modulation threshold criteria	25 %	25 %
	Addressability—horizontal	1280	1920
	Addressability—vertical	1024	1080
	# Of resolvable pixels—horizontal	1280	1528
	# Of resolvable pixels—vertical	1024	794
ASPECT RATIO			
	Decimal	1.25	1.79
	Integer	5:4	16:9

GRAY SCALE		DMD Projection System			CRT Projection System		
	Gamma	2.53			2.18		
		luminance	x	y	luminance	x	y
	Gray Scale Value=940	44	0.324	0.363	6.4	0.318	0.315
	Gray Scale Value=815	29	0.324	0.363	4.9	0.322	0.319
	Gray Scale Value=689	18	0.324	0.363	3.5	0.325	0.320
	Gray Scale Value=564	10	0.324	0.364	2.2	0.329	0.317
	Gray Scale Value=439	4.9	0.324	0.363	1.3	0.326	0.309
	Gray Scale Value=314	1.7	0.325	0.363	0.53	0.319	0.301
	Gray Scale Value=189	0.33	0.330	0.363	0.087	0.326	0.317
	Gray Scale Value=64	0.053	0.368	0.365	0.0084	low signal	







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6. Some of these procedures will be outlined in more detail in a NIST Interagency Report (IR), "Projection Display Metrology Procedures, Tools, and Diagnostics," to be published.