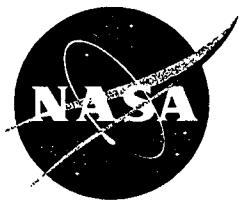
NASA/CR—2003–212258



Color and Luminance Analysis of the Space Shuttle Multifunction Display Units (MDUs)

Jeffrey W. McCandless
Ames Research Center, Moffett Field, California

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

February 2003

Acknowledgments

The section explaining the viewing angle results was written by:
Charles K. Bowen, Ph.D. at NASA Johnson Space Center

Data collection and analysis were performed with the assistance of:
Larry E. Arend, Ph.D. at NASA Ames Research Center
Charles K. Bowen, Ph.D. at NASA Johnson Space Center
Robert S. McCann, Ph.D. at NASA Ames Research Center
Michele H. Segal at NASA Johnson Space Center
Charles D. Wheelwright at NASA Johnson Space Center

Use of the lab for data measurement was arranged with the support of:
Brent H. Bynum at NASA Johnson Space Center

Available from:

NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076-1320
301-621-0390

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-605-6000

ABSTRACT

Overview

The purpose of this evaluation is to measure and analyze the colors that can be shown on the Multifunction Display Units (MDUs) of the Space Shuttle cockpit. The evaluation was conducted in the JSC Avionics Engineering Laboratory (JAEL) in building 16A at NASA Johnson Space Center. The JAEL contains a suite of 11 MDUs, each of which can be configured to show colors based on input values of the MDU red, green and blue (RGB) channels. Each of the channels has a range of 0 to 15. For example, bright green is produced by setting RGB to 0,15,0, and orange is produced by setting RGB to 15,4,0. The Cockpit Avionics Upgrade (CAU) program has specified the RGB settings for 14 different colors in the Display Design document (Rev A, 29 June 2001). The analysis in this report may help the CAU program determine better RGB settings for the colors.

Color and luminance measurements were taken with a Photo Research Colorimeter PR-650 SpectraScan and two Minolta Luminance Meters LS-100. Color coordinates were measured in units of x and y on the Commission Internationale d'Eclairage (CIE) chart, and luminance values were measured in units of nits (also known as candelas per meter squared).

Key Findings

- The color and luminance values saturate starting at level 9. For example, the color and luminance are constant for RGB values of 0,9,0 followed by 0,10,0 and continuing through 0,15,0.
- Even when all channels are set to 0, the screen is not black. Instead, it has a dark blue color with a residual luminance of about 2 nits.
- For the 14 colors selected for CAU program, viewing angle has a negligible effect on all colors except orange. The appearance of orange shifts from yellow to orange to red depending on viewing angle. Operationally, however, this shift is probably not critical because orange, red and yellow each represent an off-nominal condition that the crew should attend to.
- The colors remain constant regardless of their position on the screen (e.g., upper left corner versus center of the screen).
- The brightness knob setting has a negligible effect on the chromaticity values. As expected and desired, the brightness knob setting markedly affects luminance.
- Color discriminability is severely degraded when the MDU is illuminated by a sunlamp.
- The measurements were approximately constant across different MDUs.

Recommendations

- Currently, the CAU program defines red as RGB=15,0,0. Because its luminance is so low (about 65 nits compared with white which is 232 nits), red should be reconsidered with RGB coordinates of 15,1,1. The goal is to increase its brightness while maintaining its discriminability.

- Currently, the CAU program defines light gray as RGB=7,7,12. Because the channels saturate at level 9, the current setting for light gray may be too close to white. Light gray should be reexamined with RGB set to lower values such as 6,6,6.
- Currently, the CAU program defines pink as RGB=15,11,15 (which has nearly identical characteristics as white). Pink should be replaced with an alternative like purple (RGB=6,0,6).
- Currently, the CAU program defines brown as RGB=13,3,2 (which is similar to orange). Because this is a color with limited usage (like pink), it may be best to eliminate it altogether.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

TABLE OF APPENDICES

1. INTRODUCTION

NASA is currently upgrading the cockpit of each Space Shuttle orbiter with the Multifunction Electronic Display System (MEDS). Included in each MEDS cockpit are eleven liquid crystal displays (LCDs) which replace the four monochrome cathode ray tube screens of the original cockpit. Each LCD is called a Multifunction Display Unit (MDU). The Cockpit Avionics Upgrade (CAU) program at NASA Johnson Space Center (JSC) is redesigning the display formats shown on the MDUs to take advantage of their color and graphical capabilities. The color and luminance characteristics of the MDUs have been specified to a certain degree in the MEDS System Design Review (SDR) #1 (October 3, 1996) and the MEDS SDR #2 (July 10 and 11, 1997). The purpose of this evaluation is to provide a more comprehensive analysis of the colors that can be presented on the MDUs.

2. METHODS

2.1 Location and Dates

The evaluation was conducted in the JSC Avionics Engineering Lab (JAEL) in building 16A, room 1030 at NASA JSC over three periods:

- December 4-6, 2001
- January 22, 2002
- February 5, 2002.

2.2 Equipment

Color and luminance measurements were taken with a Photo Research Colorimeter PR-650 SpectraScan and two Minolta Luminance Meters LS-100. Color coordinates were measured in units of x and y on the Commission Internationale d'Eclairage (CIE) chart. (More details about the CIE are in Appendix C.) Luminance values were measured in units of nits (also known as candelas per meter squared). All MDUs tested were manufactured by Hosiden, which produces the same MDUs for the Space Shuttle orbiters.

2.3 Conditions

The data and associated results are in the following order:

- Condition #1: Baseline
- Condition #2: Viewing position

- Condition #3: Screen coordinates
- Condition #4: Setting of brightness knob on the MDU
- Condition #5: Sunlamp
- Condition #6: MDU comparison

3. RESULTS

3.1 Condition #1: Baseline

3.1.1 Setup

The setup conditions were as follows:

- Meter type: Photo Research Colorimeter PR-650 SpectraScan
- Meter position (with respect to screen center): 0 inches to the left, 0 inches up, 31 inches back
- Meter target (aim-point): center of screen
- Brightness knob: High
- Sunlamp: Off
- MDU tested: AFD 1

3.1.2 Luminance Results

The following plot shows luminance as a function of input level for each of the three channels. For example, the bottom curve (blue channel) represents luminance for 16 points starting with RGB=0,0,0 followed by RGB=0,0,1 and continuing up to RGB=0,0,15. The top curve (all channels) represents luminance as all channels are increased simultaneously. The curve is initiated at RGB=0,0,0, followed by RGB=1,1,1 and continuing up to RGB=15,15,15.

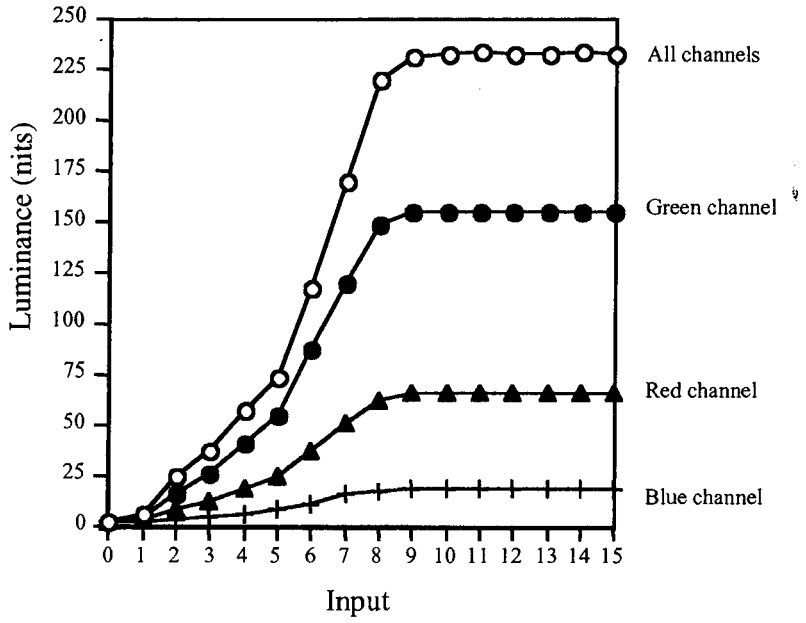


Figure 1. Luminance as a function of input

The plot has two notable points:

1. The luminance at RGB=0,0,0 is not zero. As a result, the background with zero input is not black. In fact, it appears dark blue. The CIE color coordinates of the background (measured at RGB=0,0,0) are x=0.200 and y=0.152.

2. The luminance saturates starting at input level 9. Ideally, the luminance would increase monotonically with input level. This characteristic conflicts with requirement 3.2.1.5.2.5 in SDR #1 (October 3, 1996), which states "The MDU shall be capable of 16 levels of gray, distributed uniformly, in each of the primary colors (R, G, B)." The results from the current evaluation in JAEL indicate that the levels are not distributed uniformly, as shown in Figure 1.

The associated data are listed below.

Table 1. Measurements from equal input channel values. CIE Y represents the luminance data shown in the top curve of Figure 1. CIE x,y are chromaticity values in Figure 3.

Input			**Output**		
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	15	15	0.356	0.367	232
14	14	14	0.356	0.367	233
13	13	13	0.356	0.367	232
12	12	12	0.356	0.367	232

11	11	11	0.356	0.366	233
10	10	10	0.356	0.366	232
9	9	9	0.356	0.365	231
8	8	8	0.357	0.366	219
7	7	7	0.363	0.370	170
6	6	6	0.371	0.377	117
5	5	5	0.376	0.380	72.8
4	4	4	0.372	0.375	56.3
3	3	3	0.354	0.354	37.5
2	2	2	0.355	0.349	23.8
1	1	1	0.327	0.280	5.97
0	0	0	0.200	0.152	2.02

Table 2. Measurements from non-equal input channel values. CIE Y are luminance values for the red, green and blue curves in Figure 1. CIE x,y are chromaticity values in Figure 3.

Input			**Output**		
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	0	0	0.615	0.327	65.4
14	0	0	0.616	0.327	65.3
13	0	0	0.616	0.327	65.2
12	0	0	0.616	0.327	65.3
11	0	0	0.616	0.327	65.3
10	0	0	0.616	0.327	65.2
9	0	0	0.615	0.327	65.3
8	0	0	0.615	0.327	62.3
7	0	0	0.611	0.324	50.9
6	0	0	0.603	0.318	37.4
5	0	0	0.582	0.307	24.3
4	0	0	0.562	0.298	18.7
3	0	0	0.513	0.280	11.8
2	0	0	0.462	0.260	7.99
1	0	0	0.312	0.194	3.31
0	15	0	0.315	0.597	155
0	14	0	0.315	0.597	155
0	13	0	0.314	0.597	155
0	12	0	0.315	0.596	155
0	11	0	0.315	0.597	155
0	10	0	0.315	0.597	155
0	9	0	0.315	0.597	155
0	8	0	0.315	0.596	148
0	7	0	0.317	0.593	120
0	6	0	0.319	0.584	86.4
0	5	0	0.318	0.563	54.6
0	4	0	0.315	0.545	41.2
0	3	0	0.298	0.502	25.4
0	2	0	0.283	0.449	15.5
0	1	0	0.237	0.251	4.09

0	0	15	0.146	0.085	18.4
0	0	14	0.146	0.085	18.4
0	0	13	0.146	0.085	18.4
0	0	12	0.146	0.085	18.4
0	0	11	0.146	0.085	18.4
0	0	10	0.146	0.085	18.4
0	0	9	0.146	0.085	18.4
0	0	8	0.146	0.088	16.5
0	0	7	0.146	0.090	15.4
0	0	6	0.146	0.100	11
0	0	5	0.151	0.113	7.51
0	0	4	0.154	0.117	6.07
0	0	3	0.160	0.113	4.42
0	0	2	0.170	0.127	3.24
0	0	1	0.199	0.164	2.09

3.1.3 General Color Results

Color components are typically shown on a standard CIE chart, which is a widely-used and accepted means of showing color information. The CIE x,y plot is shown below and discussed in detail in Appendix C.

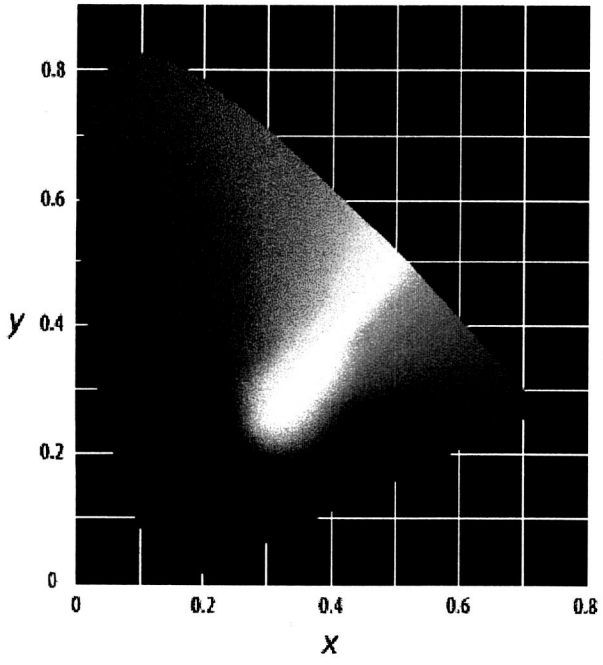


Figure 2. CIE plot

The following plot shows CIE x,y coordinates as the input value is varied. These data points represent the CIE x,y values from Table 1 and Table 2.

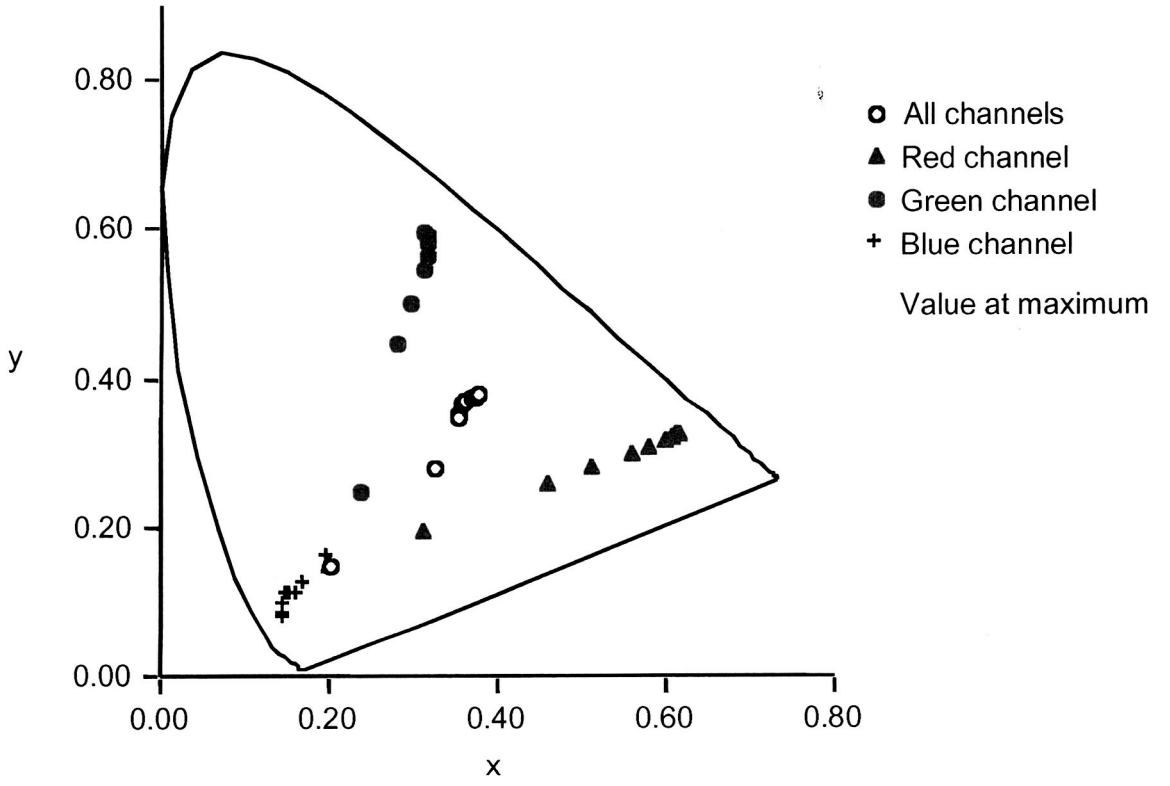


Figure 3. CIE plot showing color shifts as input level is varied.

Ideally, the color components would remain constant (meaning all data on the plot would be clustered within the four small squares). However, as the input value is lowered from 15 to 0, the color coordinates shift towards the center of the CIE x,y plot. For example, the red triangles show the CIE x,y components as the channel setting is changed from RGB=15,0,0 to RGB=14,0,0 to RGB=13,0,0 and on down to RGB=1,0,0. As expected, the luminance value decreases as the setting of the red channel is reduced from 15 down to 1. (Luminance is not shown on Figure 3.) However, the color components (CIE x,y) should remain constant (in the same square in Figure 3). Instead, the color components shift toward to blue region as the setting of the red channel is reduced.

3.1.4 Color Results for CAU Specifications

The following table shows the results for the colors selected for the CAU upgrades.

Table 3. Cockpit Avionics Upgrade colors. (The RGB specification for each color is specified in the Display Design document, Rev A, 29 June 2001.)

Input				Output		
Name	**Red**	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
1. Black	0	0	0	0.200	0.152	2.02
2. Dark gray	2	2	6	0.246	0.221	31.1
3. Light gray	7	7	12	0.342	0.342	187
4. White	15	15	15	0.356	0.367	232
5. Orange	15	4	0	0.545	0.404	107
6. Red	15	0	0	0.615	0.327	65.4
7. Yellow	15	15	0	0.453	0.490	219
8. Cyan	0	15	15	0.240	0.371	173
9. Magenta	15	0	15	0.377	0.203	81.5
10. Light green	0	15	0	0.315	0.597	155
11. Dark green	0	4	0	0.315	0.545	41.2
12. Blue	0	0	15	0.146	0.085	18.4
13. Pink	15	11	15	0.356	0.363	230
14. Brown	13	3	2	0.542	0.359	90.2

The following table (from the Display Design document, Rev A, 29 June 2001) specifies the colors MDU components and sample usage.

Table 4. CAU Colors

Sample	CAU Name	MDU value (requirements) (0-15)			PowerPoint value (0-255) (guidelines)			Sample Uses (Guidelines) [SRS Names & Abbreviations]
		R	G	B	R	G	B	
	Black	0	0	0	0	0	25	Text on light backgrounds. Halos. [Background, Bkgd] [Blanked Data, Blank]
	Dark Gray	2	2	6	60	60	80	Display region separator lines. Graphical elements which are "off". [Dynamic Off, Dyn Off]
	Light Gray	7	7	12	180	180	200	Non-dynamic text (i.e. data labels). Scales, ticks, scale labels, thermometer outlines. [Label, Lbl]
	White	15	15	15	255	255	255	Graphical elements which are "on". Nominal data & bugs. EK labels which only change menus. Advisory alerts. Display format Focus indicator. [Dynamic, Dyn]

	Orange	15	4	0	255	128	0	BFS "disagrees". Background for "BFS-engaged" flag and BFS pre-engage title bar. [BFS]
	Red	15	0	0	255	0	0	Off-nominal data (Emergency, Warning). Failure indications. Associated graphical elements and flags. [Warning, Warn]
	Yellow	15	15	0	255	255	0	Off-nominal data (Caution). Failure indications. Associated graphical elements and flags. [Caution, Caut]
	Cyan	0	15	15	0	255	255	Undetermined state: missing data & dilemma. [Missing, Miss], [Dilemma, Dil]
	Magenta	15	0	15	255	0	255	Targets. Action Alerts. [Target, Tgt]
	Light Green	0	15	0	0	255	0	Display title. EK labels which change formats. Selected item background, item entry box. Entered data (pre "Ent"). Hardware (MDU) focus indicator [Selected, Sel]
	Dark Green	0	4	0	0	160	0	Unselected item numbers [Item Number, Item]
	Blue	0	0	15	0	0	255	Special use [Secondary PL, Sec PL]
	Pink	15	11	15	220	150	220	Special use
	Brown	13	3	2	190	50	30	Special use

3.2 Condition #2: Viewing Position

3.2.1 Rationale for This Condition

The viewing angle for an MDU can vary depending on a number of factors, including the crew's position in the cockpit (e.g., commander versus pilot) and the MDU being viewed. As a means of determining the approximate range of viewing angles, cockpit measurements were taken on November 30, 2001 in a Crew Compartment Trainer (CCT) in building 9 at NASA JSC, as shown in the following figure:

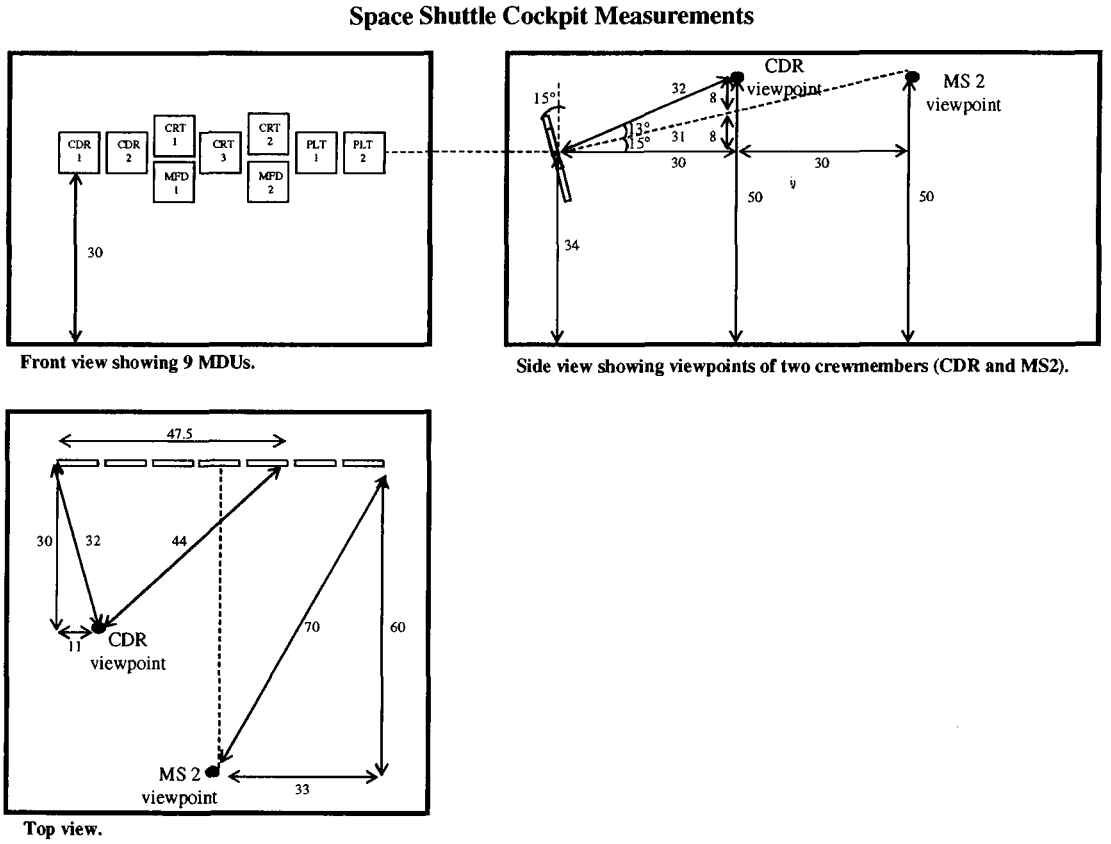


Figure 4. Cockpit measurements. Linear units are inches and angular units are degrees. CDR viewpoint refers to the commander and PLT viewpoint refers to the pilot.

The following figure shows a more detailed version of the front view.

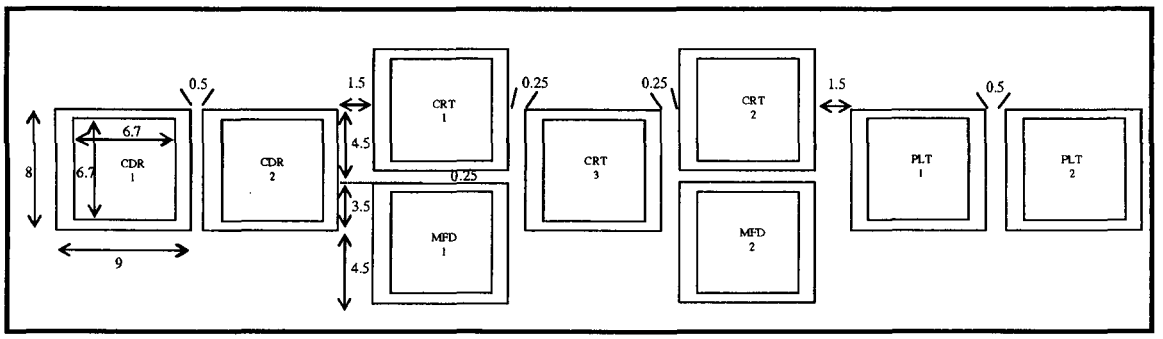


Figure 5. Cockpit measurements of the MDUs (detailed front view). All units are inches.

These measurements are approximate because the actual crewmember's viewpoint can vary depending on factors such as that crewmember's height, the elevation of the seat (which is adjustable), and whether the crewmember is leaning forward in the seat. Nevertheless, the measurements provide a reasonable basis for positioning the meters during testing in the JAEL. For condition #2, the meter was located at two positions relative to the center of the MDU screen:

- x = 35 inches left, y = 1 inch up, z = 31 inches back
  - This is defined as the Left position for the meter.
  - It represents a case where the commander views the upper right region of CRT 2.
- x = 35 inches left, y = 16 inches up, z = 31 inches back
  - This is defined as the Upper Left position for the meter.
  - It represents a case where the commander views the lower right region of MFD 2.

3.2.2 Setup

The setup conditions were as follows:

- Meter type: Photo Research Colorimeter PR-650 SpectraScan
- Meter position: varied (2 positions: Left and Upper Left)
- Meter target (aim-point): center of screen
- Brightness knob: High
- Sunlamp: Off
- MDU: AFD 1

3.2.3 Viewing Position Results

The following tables show meter readings at different positions.

Table 5. Off-axis viewing

Input				From Left			From Upper Left		
Name	Red	Green	Blue	CIE x	CIE y	CIE Y	CIE x	CIE y	CIE Y
1. Black	0	0	0	0.254	0.216	1.67	0.259	0.251	2.97
2. Dark gray	2	2	2	0.326	0.321	11.8	0.332	0.328	15
3. Light gray	5	5	7	0.290	0.274	43.3	0.321	0.312	57.7
4. White	15	15	15	0.380	0.346	97.2	0.353	0.352	86.8
5. Orange	15	4	0	0.533	0.409	49.8	0.497	0.433	55.2
6. Red	15	0	0	0.619	0.324	28.6	0.598	0.322	26.4

7. Yellow	15	15	0	0.455	0.486	91.6	0.452	0.480	80.3
8. Cyan	0	15	15	0.227	0.351	72	0.232	0.360	62.5
9. Magenta	15	0	15	0.369	0.193	35.8	0.376	0.203	32.1
10. Light green	0	15	0	0.305	0.600	64.6	0.305	0.585	56.9
11. Dark green	0	4	0	0.298	0.547	20.9	0.303	0.545	28.5
12. Blue	0	0	15	0.149	0.083	8.68	0.155	0.099	8.78
13. Pink	15	11	15	0.348	0.346	97.2	0.353	0.352	86.8
14. Brown	13	3	2	0.520	0.350	42.1	0.492	0.353	41.7

The following table shows the maximum difference among the three viewing positions (normal from Condition #1, Left and Upper Left from Condition #2).

Table 6. Maximum Difference in CIE coordinates among the 3 viewing positions

Input				**Max diff for 3 positions**			
Name	**Red**	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**	**Avg x,y**
1. Black	0	0	0	0.058	0.100	1.300	0.079
2. Dark gray	2	2	2	0.030	0.030	12.100	0.030
3. Light gray	5	5	7	0.031	0.038	14.400	0.035
4. White	15	15	15	0.035	0.021	145.200	0.028
5. Orange	15	4	0	0.048	0.029	57.200	0.039
6. Red	15	0	0	0.021	0.005	39.000	0.013
7. Yellow	15	15	0	0.003	0.010	138.700	0.007
8. Cyan	0	15	15	0.013	0.020	110.500	0.017
9. Magenta	15	0	15	0.008	0.010	49.400	0.009
10. Light green	0	15	0	0.010	0.015	98.100	0.013
11. Dark green	0	4	0	0.017	0.002	20.300	0.010
12. Blue	0	0	15	0.009	0.016	9.720	0.013
13. Pink	15	11	15	0.008	0.017	143.200	0.013
14. Brown	13	3	2	0.050	0.009	48.500	0.030

The right column in Table 6 indicates that the largest shift in CAU colors occurs for black (the background color). Among the remaining colors, orange is the most affected by viewing angle. Perceptually, it appears as yellow or red as the viewing angle is changed. The variation in orange can reduced by shifting its coordinates from RGB=15,4,0 to RGB=15,3,0. However, the drawback is that, subjectively, orange appears too similar to red if its green component is reduced. The alternative of shifting RGB to 15,5,0 has only a negligible improvement in the stability of the color as viewing angle is changed. Fortunately, the colors orange, red and yellow all refer to classes of malfunctions. Regardless of the exact color, the crew needs to attend to the associated malfunction.

3.2.4 Viewing Position Explanation

In general, the colors produced by the liquid crystal display (LCD) exhibit stable spectra with changes in viewing angle relative to the front surface of the LCD. A notable exception to this pattern was found in the case of orange, having RGB=15,4,0. As the observer moves from left to right, the hue shifts from red

through orange to yellow. A similar characteristic is observed with vertical observer displacements. The shift in perceived color corresponding to the spectral change with position is great enough to raise concerns that the orange color may be confused with red or yellow, depending on the location of the user with respect to the LCD. The following qualitative explanation of this effect is based on the geometry of the filters used in the display.

In general, all LCDs consist of a backlit array of adjustable "valves" with overlying red, green, and blue transmission filters. Each pixel consists of a minimum of three valve/filter combinations – one of each color. In the case of the MDU display, however, each pixel is produced by combining the light through nine valve/filter combinations. Each valve is implemented as an electronically controllable liquid crystal polarizing light attenuator. Transmission through the valve is controlled in proportion to the R, G, or B signal applied to it. For the MDU, a value of 15 results in maximum transmission, whereas a value of zero approximates complete occlusion of light from the source.

A hypothetical geometry for an MDU pixel is shown in the following figure. This structure is an example of the "multigap" filter, in which the thickness of the filters is varied by color. The distances traveled by the light waves after exiting the filters is set to an integer number of wavelengths for the filter color. The filters are arranged on a variable thickness transparent substrate, which conducts signals to one end of the liquid crystal channels comprising the valves. The square colored filter patches in each layer are arranged in diagonal rows across the layer. When superimposed and viewed normal to the display, each pixel is comprised of three rows and three columns of three cells. Rows and columns of cells have the same staggered sequence of red, green, and blue colors. Ideally the filters should be implemented to avoid registration and parallax effects. The variation in thickness of the filters and the transparent conductive layers overlying the liquid crystal layer provides the key to the following explanation. For the sake of simplicity, the effects of differences in refractive indices among the display materials are neglected.

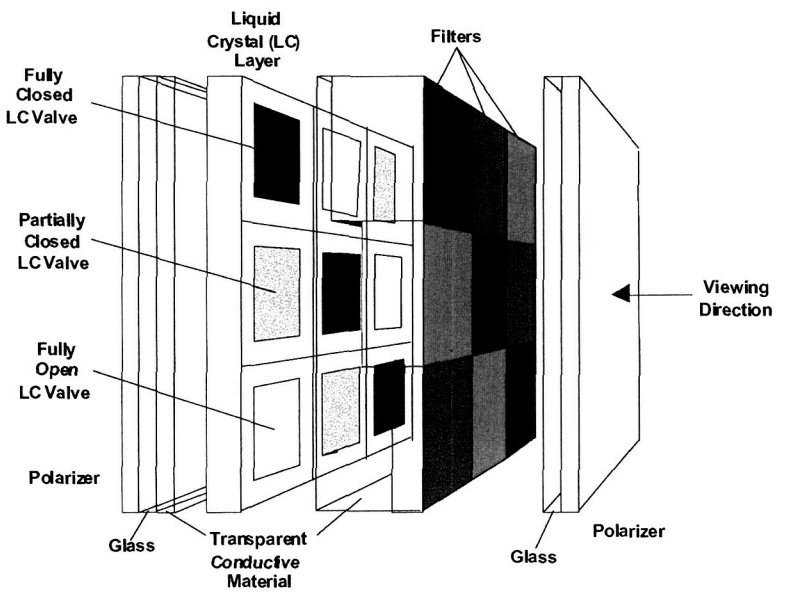


Figure 6. Schematic representation of components for a single MDU pixel producing RGB=15,4,0 (orange).

The ideal condition for each valve/filter channel is for the light rays passing through the conductive transparent layer and filter to be parallel and perfectly aligned with the edges of the valve channel. This arrangement ensures that no stray light passes from the valve to the outer display surface. The variable thickness of the filter array, however, allows the possibility of light leakage among the various layers. Light rays passing through a filter and intercepting a second filter are assumed to be totally absorbed. Some possible spurious ray paths resulting from parallax and the multigap filter geometry under are illustrated in the following two figures. Varying the relative spacing among filters and valves may significantly vary the effects from those shown in the figures.

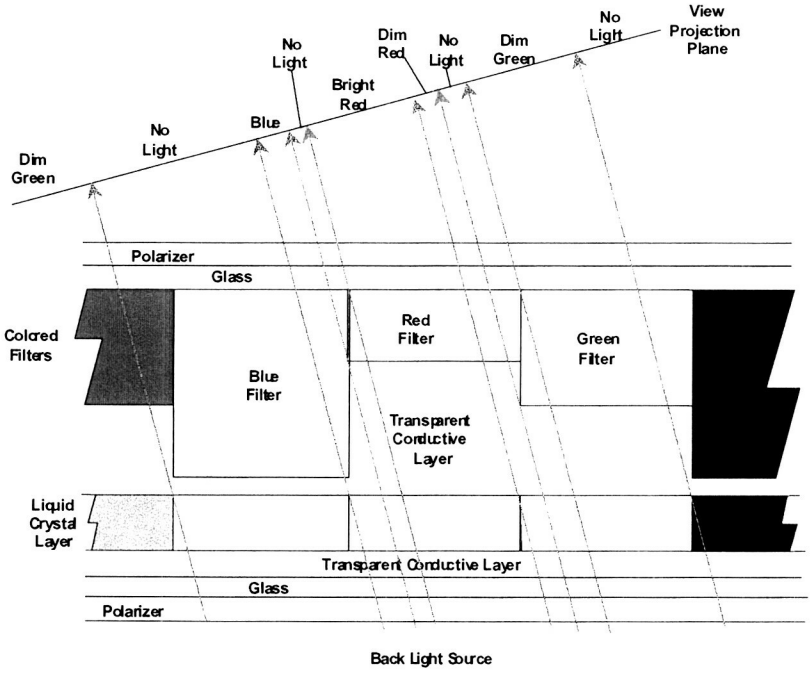


Figure 7. Light ray paths through a single row of LCD channels as viewed 15 degrees to the left of center for RGB=15,4,0.

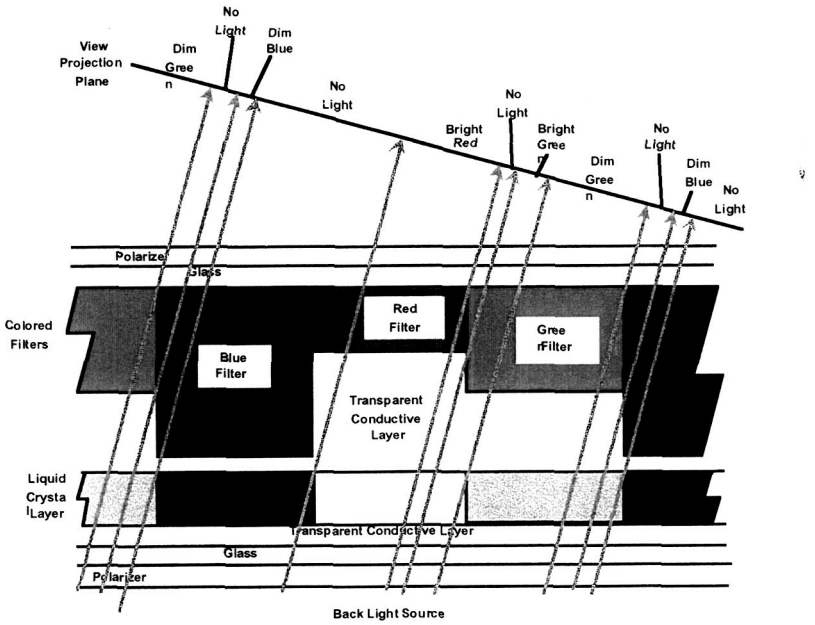


Figure 8. Light ray paths through a single row of LCD channels as viewed 15 degrees to the right of center for RGB=15,4,0.

The effects of interaction between LCD elements on perceived color may be visualized by considering the paths of parallel rays emitted from the shutter array through the filter layers. These rays may all be assumed parallel to the viewer's line of sight, provided that the viewing distance is large compared to the spacing of the pixels and the display area considered is small. The contributions of various rays to the perceived LCD color(s) may be estimated by considering the areas they intercept over a view projection plane placed perpendicular to the ray paths. The above figures model the effects of focusing on a small portion of the MDU screen, maintaining a vertical viewing angle (measured relative to the normal to the screen surface) of zero, and pivoting in the horizontal plane 15 degrees left or right.

The above figures show a transverse perpendicular section through a single row of cells set for RGB=15,4,0. When viewed from an angle left or right of the surface normal, the adjacent filters interfere somewhat to reduce the display illumination. With the line of sight deviated 15 degrees to the left or right, the brightly lighted red areas of the viewing plane and the more dimly illuminated green areas are essentially equal. The reduction in light reaching the view projection plane due to interception by two filters is the same in both cases. The differences between the perceived colors between the left and right viewing positions may be attributable to the differences in amounts of unintended light leaked through the green and blue filters. When viewed from the left (Figure 7), a small proportion of the bright light from the red channel valve passes through the blue filter, while a small amount of the attenuated light from the green channel leaks through the red filter. The overall effect of the additional red light is to make the pixel color appear more red than the nominal orange color seen normal to the display.

In contrast, when the display is viewed from the right position (Figure 8), a small proportion of the green channel's attenuated light is leaked through the blue filter, while a small amount of the red channel's bright light passes through the green filter. Since the human visual system is most sensitive to the green

portion of the spectrum, the overall effect in the right viewing position is a marked shift in the perceived color from the intended orange toward yellow.

3.3 Condition #3: Screen Position

3.3.1 Setup

The setup conditions were as follows:

- Meter type: Photo Research Colorimeter PR-650 SpectraScan
- Meter position (with respect to screen center): 0 inches to the left, 0 inches up, 31 inches back
- Meter target (aim-point): varied
- Brightness knob: High
- Sunlamp: Off
- MDU: AFD 1

3.3.2 Screen Position Results

The mean CIE x,y standard deviation is 0.0035, and the mean CIE Y standard deviation is 11.2 nits. These values were stable. The data are listed below. (Screen coordinates are measured with respect to the upper left corner of the screen.)

Table 7. Data across screen position

Display Driver			**Screen Pos #1 (left upper) (500,500) CS-100A Measurements**		
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	15	15	0.3537	0.3724	244.0
6	6	6	0.3698	0.3864	126.0
15	0	0	0.6086	0.3405	71.4
6	0	0	0.5969	0.3342	41.8
0	15	0	0.3091	0.6031	163.0
0	6	0	0.3135	0.5946	92.6
0	0	15	0.1426	0.0851	18.2
0	0	6	0.1457	0.1009	11.2
Display Driver			**Screen Pos #2 (center upper) (2300,500) CS-100A Measurements**		

Red	Green	Blue	CIE x	CIE y	CIE Y
15	15	15	0.3511	0.3716	235.0
6	6	6	0.3642	0.3841	127.0
15	0	0	0.6082	0.3450	68.7
6	0	0	0.6031	0.3377	41.1
0	15	0	0.3088	0.6061	158.0
0	6	0	0.3141	0.6002	93.5
0	0	15	0.1427	0.0840	17.4
0	0	6	0.1435	0.0964	11.0

Display Driver	Screen Pos #3 (right upper) (4100,500) CS-100A Measurements				
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	15	15	0.3550	0.3773	223.0
6	6	6	0.3690	0.3903	121.0
15	0	0	0.6058	0.3426	64.3
6	0	0	0.5982	0.3347	39.1
0	15	0	0.3094	0.6057	151.0
0	6	0	0.3151	0.5967	90.2
0	0	15	0.1430	0.0863	16.3
0	0	6	0.1459	0.1007	10.5

Display Driver	Screen Pos #4 (left middle) (500,2300) CS-100A Measurements				
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	15	15	0.3471	0.3657	285.0
6	6	6	0.3602	0.3791	158.0
15	0	0	0.6077	0.3413	82.7
6	0	0	0.5987	0.3357	51.3
0	15	0	0.3053	0.6042	190.0
0	6	0	0.3094	0.5975	115.0
0	0	15	0.1429	0.0831	22.1
0	0	6	0.1457	0.0966	14.4

Display Driver	Screen Pos #5 (right middle) (4100,2300) CS-100A Measurements				
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	15	15	0.3470	0.3741	239.0
6	6	6	0.3600	0.3873	133.0
15	0	0	0.6051	0.3431	57.4
6	0	0	0.5965	0.3371	41.8
0	15	0	0.3057	0.6077	162.0
0	6	0	0.3101	0.6010	98.9
0	0	15	0.1435	0.0863	18.3
0	0	6	0.1467	0.1005	12.0

Display Driver			Screen Pos #6 (left lower) (500,4100) CS-100A Measurements		
Red	Green	Blue	CIE x	CIE y	CIE Y
15	15	15	0.3471	0.3669	215.0
6	6	6	0.3570	0.3811	113.0
15	0	0	0.5979	0.3416	61.7
6	0	0	0.5861	0.3331	37.6
0	15	0	0.3020	0.6028	146.0
0	6	0	0.3061	0.5919	86.1
0	0	15	0.1426	0.0832	17.1
0	0	6	0.1450	0.0978	11.0

Display Driver			Screen Pos #7 (center lower) (2300,4100) CS-100A Measurements		
Red	Green	Blue	CIE x	CIE y	CIE Y
15	15	15	0.3414	0.3684	216.0
6	6	6	0.3547	0.3829	115.0
15	0	0	0.5980	0.3411	61.4
6	0	0	0.5872	0.3323	37.3
0	15	0	0.3018	0.6033	146.0
0	6	0	0.3056	0.5943	87.8
0	0	15	0.1421	0.0843	17.2
0	0	6	0.1447	0.0980	11.1

Display Driver			Screen Pos #8 (right lower) (4100,4100) CS-100A Measurements		
Red	Green	Blue	CIE x	CIE y	CIE Y
15	15	15	0.3432	0.3770	194.0
6	6	6	0.3564	0.3901	100.0
15	0	0	0.5909	0.3413	54.6
6	0	0	0.5750	0.3320	32.6
0	15	0	0.3018	0.6037	134.0
0	6	0	0.3051	0.5909	77.9
0	0	15	0.1440	0.0897	15.6
0	0	6	0.1481	0.1073	10.2

3.4 Condition #4: Brightness knob setting

3.4.1 Setup

The setup conditions were as follows:

- Meter type: Photo Research Colorimeter PR-650 SpectraScan
- Meter position (with respect to screen center): 0 inches to the left, 0 inches up, 31 inches back
- Meter target (aim-point): center of screen
- Brightness knob: Medium and low
- Sunlamp: Off
- MDU: AFD 1

3.4.2 Brightness Knob Results

The mean CIE x,y standard deviation is 0.0048, and the mean CIE Y standard deviation is 53.7 nits. Not surprisingly, the luminance (CIE Y) values changed substantially as the brightness knob is rotated. The data are listed below.

Table 8. Brightness knob data

Display Driver			Medium Brightness (about 80% of max) CS-100A Measurements		
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	15	15	0.3494	0.3549	66.80
6	6	6	0.3649	0.3702	37.30
15	0	0	0.6011	0.3403	21.10
6	0	0	0.5908	0.3335	13.30
0	15	0	0.3025	0.5903	42.70
0	6	0	0.3064	0.5810	26.00
0	0	15	0.1418	0.0868	5.76
0	0	6	0.1450	0.1008	3.72
Display Driver			**Low Brightness (about 40% of max) CS-100A Measurements**		
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	15	15	0.3590	0.3621	4.34
6	6	6	0.3781	0.3782	2.52
15	0	0	0.6135	0.3390	1.42
6	0	0	0.6023	0.3341	0.91
0	15	0	0.3049	0.6004	2.85
0	6	0	0.3010	0.5987	1.79
0	0	15	0.1406	0.0895	0.37
0	0	6	0.1374	0.1050	0.24

3.5 Condition #5: Sunlamp

3.5.1 Setup

The setup conditions were as follows:

- Meter type: Photo Research Colorimeter PR-650 SpectraScan
- Meter position (with respect to screen center): 0 inches to the left, 0 inches up, 31 inches back
- Meter target (aim-point): Center
- Brightness knob: High
- Sunlamp: On
- MDU: AFD 1

3.5.2 Sunlamp Results

The mean CIE x,y standard deviation is 0.0399, and the mean CIE Y standard deviation is 58.7 nits. Not surprisingly, the variation was substantial, rendering the display virtually unusable. The data are listed below.

Table 9. Sunlamp data

Display Driver			Nearly normal angle (about 10 degrees) CS-100A Measurements		
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	15	15	0.3347	0.3520	396.00
6	6	6	0.3352	0.3526	282.00
15	0	0	0.4107	0.3258	210.00
6	0	0	0.3804	0.3221	182.00
0	15	0	0.3049	0.4344	307.00
0	6	0	0.3057	0.4022	241.00
0	0	15	0.2465	0.2353	153.00
0	0	6	0.2676	0.2672	145.00
Display Driver			**Moderate angle (about 45 degrees) CS-100A Measurements**		
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	15	15	0.3431	0.3607	329.00
6	6	6	0.3517	0.3666	220.00
15	0	0	0.4716	0.3356	143.00

6	0	0	0.4409	0.3328	117.00
0	15	0	0.3115	0.4915	240.00
0	6	0	0.3154	0.4578	176.00
0	0	15	0.2264	0.2003	88.00
0	0	6	0.2533	0.2399	80.90

Display Driver			**Nearly parallel angle (about 80 degrees) CS-100A Measurements**		
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	15	15	0.3455	0.3684	291.00
6	6	6	0.3582	0.3808	175.00
15	0	0	0.5366	0.3402	100.00
6	0	0	0.5061	0.3352	71.80
0	15	0	0.3071	0.5543	204.00
0	6	0	0.3107	0.5267	135.00
0	0	15	0.1809	0.1409	43.90
0	0	6	0.2031	0.1794	36.20

3.6 Condition #6: Alternative MDUs

3.6.1 Setup

The setup conditions were as follows:

- Meter type: Photo Research Colorimeter PR-650 SpectraScan
- Meter position (with respect to screen center): 0 inches to the left, 0 inches up, 31 inches back
- Meter target (aim-point): Center
- Brightness knob: High
- Sunlamp: On
- MDU: Varied

3.6.2 MDU Result

The mean CIE x,y standard deviation is 0.0055, and the mean CIE Y standard deviation is 7.7 nits. Data were also taken for one display (CDR2) at different points in time.

Table 10. MDU data

Display Driver			CDR2 (5 min after it was turned on) CS-100A Measurements		
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	15	15	0.3304	0.3469	254.00
6	6	6	0.3483	0.3669	131.00
15	0	0	0.5813	0.3355	70.70
6	0	0	0.5572	0.3253	41.00
0	15	0	0.3037	0.5879	174.00
0	6	0	0.3077	0.5707	95.20
0	0	15	0.1445	0.0855	22.10
0	0	6	0.1494	0.1066	14.10

Display Driver			CDR2 (35 min after it was turned on) CS-100A Measurements		
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	15	15	0.3365	0.3712	238.00
6	6	6	0.3510	0.3839	114.00
15	0	0	0.5951	0.3419	62.90
6	0	0	0.5771	0.3304	34.00
0	15	0	0.3071	0.6034	166.00
0	6	0	0.3112	0.5904	87.00
0	0	15	0.1430	0.0829	18.50
0	0	6	0.1465	0.1004	11.20

Display Driver			MFD1 CS-100A Measurements		
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	15	15	0.3424	0.3726	257.00
6	6	6	0.3541	0.3860	145.00
15	0	0	0.6092	0.3424	69.00
6	0	0	0.6005	0.3662	42.60
0	15	0	0.3080	0.6067	174.00
0	6	0	0.3125	0.5998	106.00
0	0	15	0.1448	0.0891	20.90
0	0	6	0.1484	0.1010	13.50

Display Driver			PLT1 CS-100A Measurements		
Red	**Green**	**Blue**	**CIE x**	**CIE y**	**CIE Y**
15	15	15	0.3482	0.3696	240.00
6	6	6	0.3698	0.3886	113.00
15	0	0	0.5961	0.3355	68.70
6	0	0	0.5732	0.3205	36.00
0	15	0	0.3049	0.5985	162.00

0	6	0	0.3073	0.5785	81.20
0	0	15	0.1432	0.0887	19.10
0	0	6	0.1473	0.1107	10.50

REFERENCES

Agoston GA (1979) *Color Theory and Its Application in Art and Design.* Berlin: Springer-Verlag.

Wyszecki G and Stiles WS (1967) *Color Science: Concepts and Methods, Quantitative Data and Formulas.* New York: John Wiley & Sons, Inc.

APPENDIX A. ACRONYMS

CAU	Cockpit Avionics Upgrade
CIE	Commission Internationale d'Eclairage (International Commission on Illumination)
CIELAB	CIE L* a* b*
CIELUV	CIE L* u* v*
EDGE	Enhanced Display Generation and Evaluation
JAEL	JSC Avionics Engineering Lab
JSC	Johnson Space Center
MDU	Multifunction Display Unit
MEDS	Multifunction Electronic Display System
NASA	National Aeronautics and Space Administration
RGB	Red Green Blue
SSCC	Space Shuttle Cockpit Council

APPENDIX B. THE CIE CHROMATICITY DIAGRAM

In 1931, the CIE was established to characterize color perception for a typical normal observer. The colors can be specified by tristimulus values or chromaticity coordinates. Tristimulus values are the relative amount of imaginary primaries required to match any color with an additive color mixture. A CIE color specification based on tristimulus values is written with the variables X, Y, Z. Chromaticity coordinates are fractional amounts of the imaginary red and green primaries in the mixture. A CIE color specification based on chromaticity coordinates is written with the variables x, y, Y. The 1931 CIE Chromaticity Diagram was developed from observations with a 2 degree visual field (Agoston, 1979; Wyszecki and Stiles, 1967).

Report Documentation Page	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 2003	Technical Memorandum

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Color and Luminance Analysis of the Space Shuttle Multifunction Display Units (MDUs)	376-80-22
6. AUTHOR(S)	
Jeffrey W. McCandless	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIATION REPORT NUMBER
NASA Ames Research Center Moffett Field, California 94035-1000	IH-035
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
National Aeronautics and Space Agency	NASA/CR—2003–212258

11. SUPPLEMENTARY NOTES

Point of Contact: Key Dismukes, M/S 262-4, Ames Research Center, Moffett Field, CA 94035 (650) 604-0150

12A. DISTRIBUTION/AVAILABILITY STATEMENT	12B. DISTRIBUTION CODE
Subject Category: 18, 19 Distribution: Public Availability: NASA CASI (301) 621-0390	

13. ABSTRACT *(Maximum 200 words)*

The purpose of this evaluation is to measure and analyze the colors that can be shown on the Multifunction Display Units (MDUs) of the Space Shuttle cockpit. The evaluation was conducted in the JSC Avionics Engineering Laboratory (JAEL) in building 16A at NASA Johnson Space Center. The JAEL contains a suite of 11 MDUs, each of which can be configured to show colors based on input values of the MDU red, green and blue (RGB) channels. Each of the channels has a range of 0 to 15. For example, bright green is produced by setting RGB to 0,15,0, and orange is produced by setting RGB to 15,4,0. The Cockpit Avionics Upgrade (CAU) program has specified the RGB settings for 14 different colors in the Display Design document (Rev A, 29 June 2001). The analysis in this report may help the CAU program determine better RGB settings for the colors.

Color and luminance measurements were taken with a Photo Research Colorimeter PR-650 SpectraScan and two Minolta Luminance Meters LS-100. Color coordinates were measured in units of x and y on the Commission Internationale d'Eclairage (CIE) chart, and luminance values were measured in units of nits (also known as candelas per meter squared).

14. SUBJECT TERMS	15. NUMBER OF PAGES
Spacecraft, cockpit, displays and design	31
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited