Characterization of the Sharp Aquos 45” LCD Display

Introduction
We characterized the Sharp Aquos 45” LCD-TV and compared its performance to that of a Sony CRT, an NEC LCD monitor, and a Dell LCD monitor. Specifically, we looked at the display linearity, spectral power distribution and the individual pixel design of each device.

Experimental Setup
We worked with a Sharp Aquos 45” LCD-TV using DVI input from a Dell workstation. We took photographs with a Nikon D100 camera placed within 1” of the screen. Spectral photometry data was taken with a Photo Research PR650. We used ISET toolbox to run data gathering scripts and also wrote our own scripts for plotting gamut overlays, SPD evolutions, gamma curves, and other visual aids for the presentation.

Display Linearity
A display device’s linearity can be ascertained by measuring the additivity of pixel color components as well as the horizontal and vertical additivity of pairs of adjacent pixels set to white. [Figure 1] gives an overview of how this was done. The horizontal additivity for the Aquos is depicted in [Figure 3] and its vertical additivity is depicted in [Figure 4]. For the single pixel additivity test, we turned each sub-pixel on individually and compare the sum of all the three images with an image where all three subpixels are on simultaneously [Figure 1]. In the horizontal and vertical additivity tests, two adjacent pixels are turned on separately and then simultaneously. If the display is linear, sub-pixels should not affect the brightness of sub-pixels around it and also pixels themselves should not affect the brightness of nearby pixels.

[Table 1] shows a summary of the linearity in different regimes for the Aquos and three other devices. The Aquos has good linearity in all three categories: single pixel, horizontal, and vertical. It is comparable to the Dell LCD, which also has good linearity
across the board (single pixel additivity for the two displays is depicted in [Figure 8]). The Sony CRT has poor linearity for both the single pixel regime and the horizontal regime, as depicted in [Figure 5] and [Figure 6] respectively; however, the vertical additivity is good [Figure 7]. The NEC LCD has poor linearity only in the horizontal regime [Figure 9].

[Figure 10] compares three of the displays by testing two horizontally adjacent pixels. The first row of the figure shows just the left pixel on; the second row shows just the right pixel on; and the last row shows both pixels on. By examining the photographs, we can easily see the nonlinearities reported earlier for the Sony CRT. When only the left pixel for the CRT is on, surrounding pixels that should be completely off are visible; in fact, this color bleeding occurs in all three CRT images. Also, by visual inspection, when both pixels are on, the image combination is brighter than the two pixels turned on separately. These observations are consistent with the linearity results. While the NEC has nonlinearity in the horizontal regime, it is not obvious from these photographs.

**Pixel Design**

The pixel designs of our three comparison displays are shown in [Figure 10]. The Aquos has a unique design shown in [Figure 11]. The two prominent differences between this design and the three others are the division of each sub-pixel into two vertical parts and division of the liquid crystals into separate *domains*. When a pixel on the Aquos is ramped from black to white, between values 0-127 only one of the two halves of each sub-pixel are turned on. [Figure 12] shows a section of the display with every pixel set to a value just above 127. Notice that the second half of each sub-pixel is just starting to turn on. A checkerboard pattern forms and the sub-pixel half that is turned on alternates only in the horizontal direction. Even though essentially half of each pixel is actually on, dithering allows pixel parts to blend together in the human visual system. Sharp also claims that having more control over each sub-pixel allows reduction of motion blur. Due to time constraints this was not tested. Another claim is that having the liquid crystals be in separate *domains* allows a larger viewing angle than previous LCDs. Our experience with the Aquos substantiates this claim.

**Spectral Power Distribution**

The spectral power distribution (SPD) of a display represents the power in radiated by the screen at the various wavelengths of the visible spectrum. The SPD is used to characterize the following aspects of the display:

2. LCD Backlight Leakage.
3. Additivity of the spectral power distributions.
4. Gamma
5. Colour gamut of the screen.
The SPD for our screen was measured using the PhotoResearch PR650 spectral photometer. The Aquos LCD display was turned on for about 1 hour prior to the measurements to avoid any discrepancies present during the period when the LCD lamp warms up.

For the remaining section, “channel pixel value” refers to the unsigned 8-bit value (ranging from 0 to 255) for the specified color channel (R, G or B). “Channel color value” represents the normalized “channel pixel color”, ranging from 0.0 (channel is off) to 1.0 (channel is fully on).

Setting the level of the R, G or B channel to a value implies setting only the specified channel to a certain value and turning off the others. Setting the level of the white channel to a certain value implies setting the R, G and B channels to the specified value simultaneously. Channel saturation refers to the extent to which a channel is turned on, with 0 saturation meaning the channel is turned off and full saturation meaning that the channel is turned on fully.

**Spectral Distribution of the RGB channels**

The spectral power of each channel was measured at increments of 0.03125 of the channel pixel color starting at 0.0. This corresponds to a step size of 8 in the channel pixel value. Thus the spectral power was measured for each channel at 33 different channel pixel values.

Data plots of the SPD at select color values are shown in [Figure 13]. In each plot the red line represents the SPD for the red channel, the green line represents the green channel SPD and the blue line represents the blue channel SPD. We find that the SPD profiles for each of the channels are nearly identical at very low values (see the Section on LCD Backlight Leakage). However, they start to delineate themselves as the channel pixel values are increased. After around a channel pixel value of 64 the SPD profiles for each of the RGB channels are clearly distinguishable.

As a next step, the SPD of the white channel was measured in steps of 0.03125. Some select plots are shown in [Figure 14]. We noticed that power radiated from the screen spans over two orders of magnitude, ranging from $4.3707 \times 10^{-5}$ W/sr/m$^2$/nm (at 544 nm) to $3.00 \times 10^{-3}$ W/sr/m$^2$/nm (at 544 nm) over the entire channel color value range.

The white channel SPDs can be used to give an approximate “contrast ratio” for the screen. We calculate the $Y$ value (using the standard X, Y, Z functions) for the black screen and the peak white screen and find a ratio of approximately 1:532.

**LCD Backlight Leakage**

As mentioned previously we noticed backlight leakage for all three channels when the channel pixel color is set to 0.0. Since this corresponds to a fully black screen, the measured SPD should have been exactly 0 in ideal conditions with no backlight leakage.
Figure 15 shows the SPDs of the backlight leakage. There are two features of note here. Firstly, since the screen is turned completely black in the separate tests for the R, G and B channels, we expect the leakage to be identical. The measured SPDs show this, with some very minor discrepancies between the red, blue and green lines possibly due to some measurement equipment inaccuracies. Secondly, since the screen is turned off we do not expect any specific color’s SPD components to be dominant. This is borne out by the fact that the SPD profile for the black screen closely resembles the shape of the SPD of the fully white screen in Figure 14.

Additivity of Spectral Power Distributions

In our tests, we also found that the spectral powers of each of the individual channel SPDs add linearly when combinations of the color channels are turned on. We compared the SPDs of the white channel at specific channel color values with the sum of the SPDs of the individual R, G, and B channels at the same channel color values. The results in Figure 16 show that there is very little discrepancy between the SPDs of combinations of different channel color values to the corresponding sum of SPDs of the individual color values.

Gamma Curves

The measurement of the SPDs also allows us to calculate the gamma factor for the display also. The gamma factor, \( \gamma \), maps the channel color value (between 0.0 to 1.0) to a normalized intensity value (between 0.0 and 1.0). Given an SPD \( s \), we can get the corresponding XYZ coordinates as:

\[
\begin{bmatrix}
X_{spd} \\
Y_{spd} \\
Z_{spd}
\end{bmatrix} = \begin{bmatrix} X^T \\
Y^T \\
Z^T
\end{bmatrix} s,
\]

where \( X, Y, Z \) are the standard CIE XYZ functions. Given a vector \( Y_{samples} \in \mathbb{R}^{1 \times n} \) as the vector of values of the Y coordinate for SPDs measured at channel color values, \( C_{samples} \in \mathbb{R}^{1 \times n} \), define \( \bar{Y}_{samples} = Y_{samples} / \max(Y_{samples}) \), we have by definition:

\[
\bar{Y}_{samples} = (C_{samples})^\gamma \quad \Rightarrow \log(\bar{Y}_{samples}) = \gamma \log(C_{samples})
\]

Thus \( \gamma \) can be estimated from the data using a least squares best fit.

A plot of the raw data samples used to compute the gamma factors is shown in Figure 17. We see that the gamma data for each of the individual channels and the gray shades seem very close to each other which suggests good display characteristics. The slight discrepancies could possibly be due to differences in the R, G, and B sub-pixels or minor measurement inaccuracies. Also we find that gamma factor for the white channel is about 2.17 which is quite close the CRT typical gamma of 2.2. The measured gamma factors for the various channels are listed in Table 2.

Color Gamut
Given the SPDs for the R, G, B and white channels, it is possible to compute the chromaticity (x-y) coordinates that screen’s color gamut for different channel color values. We plot the chromaticity coordinates for the R, G, B and white channel SPDs at the color channel values from 0.0 to 1.0 in steps of 0.03125. The results are displayed in [Figure 18]. The Aquos’ chromaticity coordinates for the saturated R, G, and B channels (plotted using orange dots) define the vertices of the gamut triangle. The chromaticity coordinate for the saturated white channel (also plotted using an orange dot) lies approximately at the centroid of the gamut triangle. All four of these chromaticity points correspond well to the “idealized” R, G, B and D65 values listed in the sRGB color space standard (plotted on [Figure 18] using light blue dots). The Aquos’ chromaticity coordinates and their “idealized” sRGB values are listed in [Table 3] for comparison.

From [Figure 18] we also find that the chromaticity coordinates of each channel’s SPD vary with the channel saturation. For each channel, the sizes of the various points plotted represent the channel’s saturation level. So the chromaticity coordinates of the R, G and B channels at low saturation (small red, green and blue dots) lie very close to the chromaticity coordinate of the screen’s white point. This is due to the dominant effect of the leakage of the backlight [See Section on LCD Backlight Leakage] at low channel saturation. As the channel starts to saturate, the SPD of the channel starts to dominate, causing the chromaticity coordinate to move towards the corresponding gamut triangle vertex (and hence the plotted points get larger as they move out towards the gamut vertices).

Finally, we also compare the color gamut of the Aquos display with those of the Sony CRT TV, NEC LCD monitor and the Dell LCD monitor in [Figure 19]. The upper row of images overlays the Aquos gamut in green over the gamuts of the other displays. We find that the Aquos gamut mostly covers the gamuts of the other displays, indicating that the Aquos can display a larger range of colors. The lower row has overlays of the gamuts of the other displays over the Aquos gamut (still displayed in green). Here, it is clear that the gamut of the NEC LCD is significantly smaller than that of the Aquos. The Sony CRT gamut is marginally smaller, which shows that the Aquos’ LCD has a better color range than the CRT. The Dell LCD, which is also a relatively new monitor nearly identical to the Aquos. The Dell gamut covers the red-green side of the gamut slightly better, but the Aquos covers the blue-green side of the gamut better.

**Conclusion**

Through our experiments, the Sharp Aquos display is a high quality LCD display. The Aquos is linear in all three additivity regimes we analyzed. It has a novel pixel design with two sections per sub-pixel and separate liquid crystal domains that seem to improve viewing angle. As far as the SPDs go, they are linearly additive with a contrast ratio of approximately 532:1. The measured gamma value of ~2.17 and chromaticity values for the red, green, and white points closely match to those of the sRGB recommendations. Aquos has a superior color gamut compared to the Sony CRT and the older NEC LCD,
and is comparable to the Dell LCD. These results show how far LCD technology has come in recent years.
References

Sharp, Feng, Daly. LCD Blue Modeling and Analysis. Sharp Labs of America.


## Tables

<table>
<thead>
<tr>
<th>Display</th>
<th>Type</th>
<th>Single Pixel</th>
<th>Horizontal</th>
<th>Vertical</th>
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<tbody>
<tr>
<td>Sony</td>
<td>CRT</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>NEC</td>
<td>LCD</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
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<td>Dell</td>
<td>LCD</td>
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<td>Good</td>
<td>Good</td>
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<tr>
<td>Sharp Aquos</td>
<td>LCD</td>
<td>Good</td>
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Table 1: Linearity Problems for Display Devices

<table>
<thead>
<tr>
<th>Channel</th>
<th>Gamma Value</th>
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<tbody>
<tr>
<td>Red</td>
<td>1.9435</td>
</tr>
<tr>
<td>Green</td>
<td>2.1175</td>
</tr>
<tr>
<td>Blue</td>
<td>1.7508</td>
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<tr>
<td>White</td>
<td>2.1712</td>
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Table 2: Gamma values for different channels

<table>
<thead>
<tr>
<th>Chromaticity Point</th>
<th>Aquos Chromaticity (x, y)</th>
<th>sRGB Recommended Chromaticity (x, y)</th>
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</thead>
<tbody>
<tr>
<td>Saturated Red</td>
<td>(0.6427, 0.3385)</td>
<td>(0.6400, 0.3300)</td>
</tr>
<tr>
<td>Saturated Green</td>
<td>(0.2803, 0.6118)</td>
<td>(0.3000, 0.6000)</td>
</tr>
<tr>
<td>Saturated Blue</td>
<td>(0.1438, 0.0722)</td>
<td>(0.1500, 0.0600)</td>
</tr>
<tr>
<td>D65 (white point)</td>
<td>(0.3011, 0.3114)</td>
<td>(0.3127, 0.3290)</td>
</tr>
</tbody>
</table>

Table 3: Chromaticity coordinates of the Aquos LCD compared to the sRGB recommended values
Figures

Figure 1. Aquos Additivity Tests in Single Pixel, Horizontal, and Vertical Regimes

Figure 2. Aquos Single Pixel Additivity Results
Figure 3 Aquos Horizontal Additivity Results
Figure 4 Aquos Vertical Additivity Results

Figure 5 Sony CRT vs. Aquos: Single Pixel Regime
Figure 6 Sony CRT vs. Aquos: Horizontal Regime

Figure 7 Sony CRT vs. Aquos: Vertical Regime
Figure 8 Dell LCD vs. Aquos: Single Pixel Regime

Figure 9 NEC LCD vs. Aquos: Horizontal Regime
Figure 10 Pixel Design Comparison With Real Photographs

Figure 11 Aquos Pixel Design (photograph of single pixel)
Figure 12: Aquos pixels set at pixel value 144 in all three channels

Figure 13: RGB SPDs at independent channel pixel values: 0, 64, 128, and 256
Figure 14: White SPDs at pixel values: 0, 64, 128, and 256

Figure 15: Picture of the backlight leakage for RGB (pixel value 0)
Figure 16: Comparison of Additivity SPD (sum of R+G+B SPDs compared with White SPD)

Figure 17: Gamma curves for RGB channels and for a white screen
Figure 18: Color Gamut for the Aquos LCD display with chromaticity coordinates at varying channel pixel values.

Figure 19: Comparing display gamuts by pairs in columns. (Sony=blue, Aquos=green, NEC=red, Dell=yellow)