LCD Sunlight Readability

Introduction

The readability of an LCD in outdoor environments, in particular, under direct sunlight, depends on two factors:

1. How bright is the LCD?
2. How good is the display contrast?

First of all, everything in direct sunlight is quite bright. So, an LCD with normal brightness may appear totally black to the eyes. Second, the sunlight may reduce the image contrast to a level such that it becomes difficult to differentiate between the “white” and the “black” displayed on the screen. In both cases, the display is not easily readable.

The scientific term “luminance” is used to specify the visual brightness of an object. Luminance is measured in units of Candelas per square meter (Cd/m^2 or nits) and footlambert (fL). To convert Cd/m^2 to fL, multiply the number in Cd/m^2 by 0.2919. That is, 1 Cd/m^2 = 0.2919 fL. Luminance is also called “photometric brightness” and is therefore simplified to “brightness” in layman’s term.

The following table lists the brightness (in Cd/m^2)of some common objects measured on a bright, sunny summer day in Northern California.

Objects	Normal to Sunlight	In bright Open Shade
White Xerox paper	26,000	1,900
Magazine (white area)	28,500	2,000
(black area)	1,690	170
Standard white*	36,000	2,600

* A standard white is a white plaque that has a near 100% reflectivity.

If the sunlight reaches the objects at an angle, then the brightness of the objects is reduce according to the cosine law. That is, if the sunlight hits the object at 45^o incident angle, the brightness of the standard white is

$$36{,}000 \times \cos(45^o) = 25{,}455\ Cd/m^2$$

So, the brightness levels measured normal to the sunlight represent the maximum levels experienced in the direct sunlight.

The Screen Brightness Issue

In strong direct sunlight, the brightness of a standard white can reach 35,000 to 40,000 Cd/m^2. The brightness of the surrounding objects with other colors such as buildings, trees, etc. are generally much lower. First of all, they do not have 100% reflectivity. Second, the sunlight does not hit every object in normal direction.

In the field of professional photography, Eastman Kodak used to supply an 18% gray card that the photographer can use to determine the correct exposure. The ideal behind this is that the average brightness of typical scenes (which may include white cloud, blue sky, landscape with trees, buildings, people, etc..) is about 18% of the brightness of the standard white. So, the reflection from this gray card represents the average reflection from the scene. Therefore, the photographer can expose his film according to the brightness of this 18% gray card and obtain good pictures.

Based on the above argument, we can claim (not 100% scientific) that the average brightness of an outdoor scene can reach 6,500 Cd/m^2 (18% of 36,000 Cd/m^2). When the human eyes are adapted to such a brightness level, the “white” color displayed on a 200 Cd/m^2 LCD monitor appears extremely “black” since it is only at 3% of the average brightness of the surrounding objects.

On the other hand, a Landmark Technology sunlight readable LCD at 2,400 Cd/m^2 is at 37% of the average brightness of the surrounding. As a result, the screen looks reasonably white (or light gray). However, since the “white” displayed on the screen (at 2,400 Cd/m^2) is only at 9.2% of the brightness of the white Xerox paper, the image quality of the display is not going to be very good.

The above scenario represents the worst case where the sunlight hits the LCD at an angle nearly perpendicular. In reality, bright scenes at this extreme level occur only when you are on a beach (with white sand) or on a ski slope with a lot of snow around.

If the LCD is in an open shade with no direct sunlight. The brightness of the standard white measured on an average sunny day is about 2,500 Cd/m^2. If we apply the 18% gray card rule again, the average brightness of the surrounding objects is 450 Cd/m^2. As a result, a 2400 Cd/m^2 sunlight readable LCD looks pretty bright and will present a superb image quality. After all, it is 5 times brighter than the average surrounding objects, and the “white” displayed on the LCD screen at 2,400 Cd/m^2 is significantly brighter than the white Xerox paper.

On the other hand, with a 200 Cd/m^2 LCD monitor in the same open shade, the “white” displayed on the screen is 10 times dimming than the white Xerox paper. So, the display quality is not very satisfactory.

Since most of the outdoor scenes fall between the two cases described above, we can make the following conclusions:

1. The 2,400 Cd/m^2 sunlight readable LCD such as Landmark LM117-150XA03 looks very good for most of the outdoor scenes. The display performance becomes marginal only under the brightest outdoor environments.

2. A 200 Cd/m^2 standard LCD monitor has marginal performance even in the open shade. With any sunlight falling onto the LCD or viewing the screen against a bright background, the display performance will not be acceptable.

3. For display applications in an outdoor area with no direct sunlight, than a LCD with screen brightness between 500 - 1,000 Cd/m^2 will be acceptable. However, a 1,500 Cd/m^2 or brighter sunlight readable LCD for the same application will deliver a much better looking image.

The Display Contrast Ratio

Definition

Contrast ratio is defined as the luminance (brightness) ratio between a brighter state and a darker state on the display screen. For a color LCD, the “white” state and the “black” state are usually used to calculate the contrast ratio. That is,

Contrast ratio = CR = luminance of the “white” / luminance of the “black”

Following this definition, if the white and the black are equally bright, then CR = 1 and the display is not readable.

If we apply this equation to the test results of the magazine in Table 1, the CR of the magazine is 16.9 in direct sunlight and 11.8 in open shade. These values are quite typical for high quality printed matters on paper. A lower quality printed page such as a new paper has a typical CR about 5. On the other hand, for displays targeted primarily for entertainment and advertisement applications, image quality is the most important concern and therefore, require a high CR value.

Sometimes, CR is not a good quantity to specify the performance of a multi-color display. For example, a red character on a blue background may have a CR = 1 if the red and the blue have the same luminance level. Accordingly, the display should not be readable. However, the human eyes, being color sensitive, can read a red character against a blue background quite well. To resolve this problem, the display community has proposed the “color difference” as a more precise representation of display performance. However, CR is still widely used in specifying display performances.

The Inherent Contrast Ratio

For a given display, its CR is greatly effected by the glare (or reflection) at the front surface of the display. Therefore, we usually measure the inherent CR value of a display in a dark room. For example, if an LCD of 200 Cd/m^2 brightness has a CR (inherent) of 400, then the brightness of the white state is 200 Cd/m^2 and the brightness of the black state is 200/400 = 0.5 Cd/m^2.

The Effect of the Ambient Illumination

If we place this LCD in a well lit room, the actual CR of the screen may be much lower than its inherent CR value of 400. For example, if the ambient room light causes a glare at the front surface of the LCD that measures 20 Cd/m^2. When the screen displays a “black”, the observer sees the 0.5 Cd/m^2 “black” plus the 20 Cd/m^2 glare. Thus, the black perceived by the observer has a luminance of 20.5 Cd/m^2. By the same argument, the “white” perceived by the observer has a luminance of 220 Cd/m^2. As a result, the CR of the LCD is now:

$$CR = 220 / 20.5 = 10.7$$

which is much lower than the inherent CR of 400.

The basic physics of glare is that when light travels from media #1 to media #2, reflection occurs at the interface. If the light travels in a direction perpendicular to the interface, then the percentage of light reflected from the interface is given by the following simple equation.

$$\text{Amount of Reflection} = [(n_1 - n_2)/(n_1 + n_2)]^2 \ \%$$

Where n_1 and n_2 are the index of refraction of media #1 and media #2 respectively.

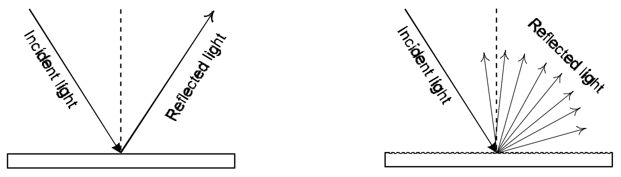
At incident angles other than perpendicular, the equation becomes quite complicated, and in general, the amount of reflection is higher.

To cite an example, when light enters a piece of glass (index of refraction = 1.5) from air (index of refraction = 1) in normal direction, the reflection at the air/glass interface is:

$$R = [(1.0 - 1.5) / (1.0 + 1.5)]^2 = 4\%$$

When the light reaches the other side of the glass and enters back to the air, the reflection at this second interface is again 4%. As a result, the total reflection caused by a piece of glass in front of a display is about 8%.

Now, the question is how this 8% reflection is distributed in the space. If both surfaces of this piece of glass are smooth, the reflection from the glass would be specular. Specular reflection is what you would get from a mirror. On the other hand, if the glass has an anti-glare finishing, then the reflection from the glass will be randomly distributed into a cone angle in a situation more like what you get from a piece of paper.



Specular reflection from smooth surfaces

Random reflection from an anti-glare (rough) surface

When looking directly against the reflection from a specular surface, the observer sees an image of the light source. If this light source is the sun, the observed image is extremely bright even the reflectivity is only 4%. On the other hand, if the reflective surface is rough or with an anti-glare coating, the reflected light is distributed over a wide angular cone. As a result, at any given viewing direction, the amount of light reaching the observer’s eyes is significantly reduced. To cite an example, if the 4% reflected sunlight is distributed into a cone similar to those from a standard white, the observer will see a glare of only 1,400 Cd/m^2 (which is 4% of the brightness of the standard white in direct sunlight). Reflections from most of the physical surfaces are somewhat between specular and diffusing.

An anti-glare surface is very effective to improve the viewability of an LCD for indoor applications. In an indoor environment, the brightness of a standard white is about 300 Cd/m^2. So a 4% reflection from an anti-glare perfect diffusive surface is about 12 Cd/m^2. If we still using the 200 Cd/m^2 LCD with 400:1 contrast ratio as an example, the brightness of the black is now 12.5 Cd/m^2, and the brightness of the white is 212 Cd/m^2. Thus, the contrast ratio of the display is 17. Now if the front surface of the LCD is specular and if the observer views the screen directly against the reflection from a fluorescent light fixture. The 4% reflection from the surface can result a glare of 100 Cd/m^2. Therefore, the contrast ratio of the LCD is 300/100.5 = 2.99 which is not good at all.

On the other hand, in outdoor environments, in particular under direct sunlight, an anti-glare surface can cause more trouble than a specular reflective surface. As described before, the brightness of the reflected light from a perfectly diffusive surface at 4% reflectivity can reach 1,400 Cd/m^2 in the extreme case. At this glare level, a 200 Cd/m^2 LCD is completely washed out. Even the Landmark Technology 2,400 Cd/m^2 sunlight readable LCD module will only maintain a contrast ratio of 2.7. On the other hand, if the reflection from the LCD is specular, the sunlight is reflected toward a specific direction. The observer will avoid to view the LCD from this direction since the reflected sunlight is way too bright to be comfortable. At the other viewing angles, there is some residual glare due to some diffusive reflections caused by surface contaminants, scratches, dusts, and minor index of refraction mis-matching in various films and layers of the LCD. However, with a clean display, the residual diffusive reflection is generally quite low and as a result, a good contrast ratio can be maintained.

To prove this argument with some real examples, we conducted experiments to measure the glare from the following three sunlight readable LCD modules on a very bright day where the sunlight was measured at 9,000 ft-candle (very bright).

1. Landmark Technology C073 (with Sharp LQ10D421 LCD) which has a polarizer with a smooth (specular) front surface.

2. A Landmark Technology R&D LCD module with Sharp LQ64D142. This LCD has an AR (anti-reflective) front polarizer (directly from Sharp).

3. A Landmark Technology LM073A LCD module with an AR coated film laminated onto the front polarizer which has an AG coating.

The sunlight was introduced to the LCD at 45^o off-axis angle, and the residual glare was measured at normal direction. The following are the results:

LCD Module	Front surface Type	Residual Glare Measured
C073	Smooth polarizer, no AR	355 Cd/m^2
R&D module	Factory AR polarizer	166
LM073A	AG polarizer with AR coated film laminated	375

It is obvious that the residual diffusive reflection from all three LCD modules are much less than the diffusive reflection from a module with an AG (anti-glare) polarizer. Since all three modules have a “white” luminance about 1,500 Cd/m^2, the contrast ratio of the displays are between 5 to 10, which is quite good in considering that the sunlight was very bright on the day of the experiment.

It is quite surprising that the LM073A module with a laminated AR coated film is actually worse than the C073 module with an ordinary smooth polarizer. This is perhaps due to the fact that a laminated film causes two additional interface surfaces. Even the reflection from the front surface is reduced due to the AR coating, the two additional surfaces may cause more reflections if the lamination adhesive does not have an index of refraction that matches perfectly to those of the film and the front polarizer.

The best one among the three modules tested is the 6.4" R&D module with a factory AR coated polarizer. At a sunlight level of 9,000 ft-candle, the display can still maintain a contrast ratio at 10:1!

An Actual Example

Let us show an actual example to conclude this technote. In summer of 1999, Landmark Technology conducted outdoor measurements with our C095 sunlight readable LCD module. The sunlight was introduced to the display at 45^o along the 12 o’clock direction. We tested a plain C095 module and a module that has an AR coated glass laminated onto the front polarizer. Both C095 modules were operated at a screen brightness of 1,500 Cd/m^2. At a sunlight level of 10,000 ft candles (very strong sunlight), the display contrast ratio of the two modules are:

Module	Contrast Ratio
Plain C095 with AG polarizer	5:1
C095 with laminated AR glass	11:1

As a result, it appears that an AR coated glass laminated onto an AG polarizer with a good index matching adhesive can increase the CR of the display by a factor of two or more. For more information on this test, please refer to Landmark Technote TK1199 - Sunlight Readable Color LCDs for Outdoor Applications.