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Characterising Sources of Ghosting in Time-Sequential Stereoscopic Video Displays

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ABSTRACT

A common artefact of time-sequential stereoscopic video displays is the presence of some image ghosting or crosstalk between the two eye views. In general this happens because of imperfect shuttering of the Liquid Crystal Shutter (LCS) glasses used, and the afterglow of one image into another due to phosphor persistence. This paper describes a project that has measured and quantified these sources of image ghosting and developed a mathematical model of stereoscopic image ghosting. The primary parameters which have been measured for use in the model are: the spectral response of the red, green and blue phosphors for a wide range of monitors, the phosphor decay rate of same, and the transmission response of a wide range of LCS glasses. The model compares reasonably well with perceived image ghosting. This paper aims to provide the reader with an improved understanding of the mechanisms of stereoscopic image ghosting and to provide guidance in reducing image ghosting in time-sequential stereoscopic displays.

Keywords: Stereoscopic, Liquid Crystal Shutter glasses, Ghosting, Crosstalk, Phosphor Afterglow, Shutter Leakage.

1. INTRODUCTION

One of the most common stereoscopic display techniques is the use of liquid crystal shutter (LCS) glasses in combination with the sequential display of left and right perspective images on a common Cathode Ray Tube (CRT) display (e.g. most TVs and computer monitors). When the left perspective image is displayed on the screen, the right eye cell of the LCS glasses goes opaque and the left eye cell goes clear, and vice versa for when the right perspective image is displayed. Therefore the left eye sees only left perspective images and vice versa for the right eye. If the speed of repetition is sufficiently high, the eye will not notice the alternate presentation of the images nor any flicker.

This technique is often called field-sequential or frame-sequential 3D since sequential or alternate images contain the left and right image. The term field-sequential applies to interlaced video systems and frame-sequential applies to progressive mode video displays. An overall term that can be used to describe both field- and frame-sequential systems is "time-sequential".

An unfortunate property of these types of stereoscopic displays is the presence of a low level amount of image ghosting or crosstalk. Image ghosting or crosstalk is the leakage of one eye view into the other eye. For example, the left eye should only be able to see the left perspective image, but due to crosstalk, the left eye sees a small proportion of the right perspective image.

The amount of crosstalk is typically quite low and hence is usually mostly noticed on images that exhibit high contrast. For example, where a bright object appears against a dark background.

Most of the literature on the subject of crosstalk [1,2,3,4,5,6] cites two main contributors to crosstalk:

- **Phosphor Afterglow**
  Images are formed on a CRT display when the phosphor coating on the inside of the tube fluoresces upon excitation by an electron beam. The light output of these phosphors ‘decay’ after the initial excitation instead of extinguishing immediately. This phosphor persistence (or afterglow) enables one image to persist in time so that a faint ‘afterglow image’ may still be seen when the subsequent image is being displayed on the CRT. In this way, the left perspective

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image is displayed simultaneously with an 'afterglow image' of the right perspective image, enabling the left eye to see both, and similarly for the right eye.

- **Shutter leakage**
  Due to the physical limitations of LC (liquid crystal) technology, when an LC shutter occludes an eye, it does not become totally 100% opaque. Thus if the displayed image is bright, the occluded eye may still be able to see a small percentage of the image not intended for it.

Our questions were:

- How much do phosphor afterglow and shutter leakage actually contribute to crosstalk?
- Are there any other contributors to crosstalk? Some factors that we considered were: timing of the LCS drive signal (when in the Vertical Blanking Interval the switch occurs), the nature of the signal used to drive the LCS (voltage, modulation, etc), and the field/frame rate of the CRT display. Lipton[7] also discusses angle of view through the LCS.

These questions weren't entirely addressed in the literature so we set about performing some measurements to characterise the crosstalk.

2. CROSSTALK MEASUREMENT AND MODELING

2.1 CROSSTALK MEASUREMENT

Unfortunately, it wasn't possible for us to separately measure the contribution of phosphor afterglow and incomplete extinction to ghosting directly in one measurement. Therefore we had to devise a method by which we could model the crosstalk process mathematically using the measured individual properties of the CRT phosphors and LCS glasses.

The three items that we measured to develop our model were:

- Phosphor spectral response,
- Phosphor time response, and
- LC shutter time/spectral response.

2.1.1 PHOSPHOR SPECTRAL RESPONSE

The colour image on a CRT display is constructed using three different colour phosphors: RED, GREEN, and BLUE. We used an Ocean Optics S1000 Spectoradiometer to measure the spectral output of the three colour phosphors. The results of this measurement (carried out on a selection of 11 different CRT computer monitors and TVs) are shown in Figure 1.

It can be seen that the blue and green phosphors exhibit a classic bell shape curve centred at around 450nm for blue and 520nm for green. In contrast the red phosphor has many peaks with the main peak at around 630nm. One further aspect of this result to note is the partial spectral overlap of the three phosphors.

We carried out this same measurement on 11 different CRT computer monitors and TVs in order to establish how much variation there was between different monitors. The overlaid results of all 11 CRT monitors are shown in Figure 2. We were surprised by the uniformity of the result, which obviously indicates that a standard set of phosphors is used in most CRT displays.

Note, however, that the one CRT projector that we measured had a very different spectrum than the CRT monitors that we measured. LCD displays also have a considerably different spectrum for each of the red, green and blue primaries, which is due to the entirely different display method used. However, it should be noted that LCS glasses would not normally be used with current LCD monitors.

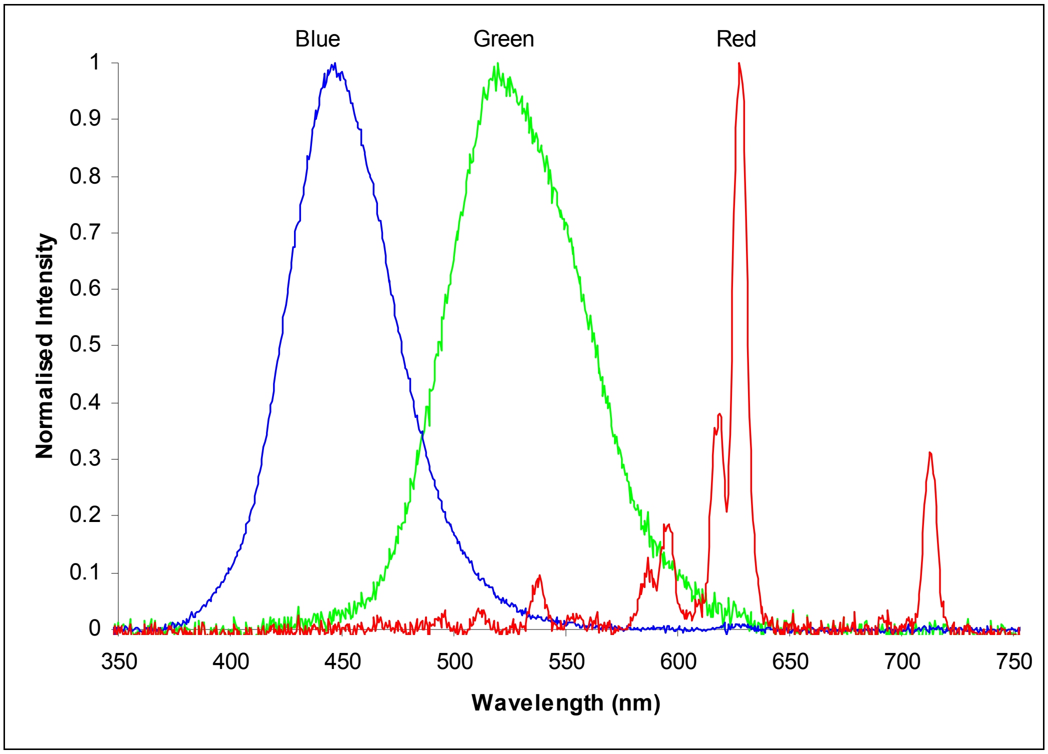


Figure 1: Spectral output of the phosphors of a typical CRT display.

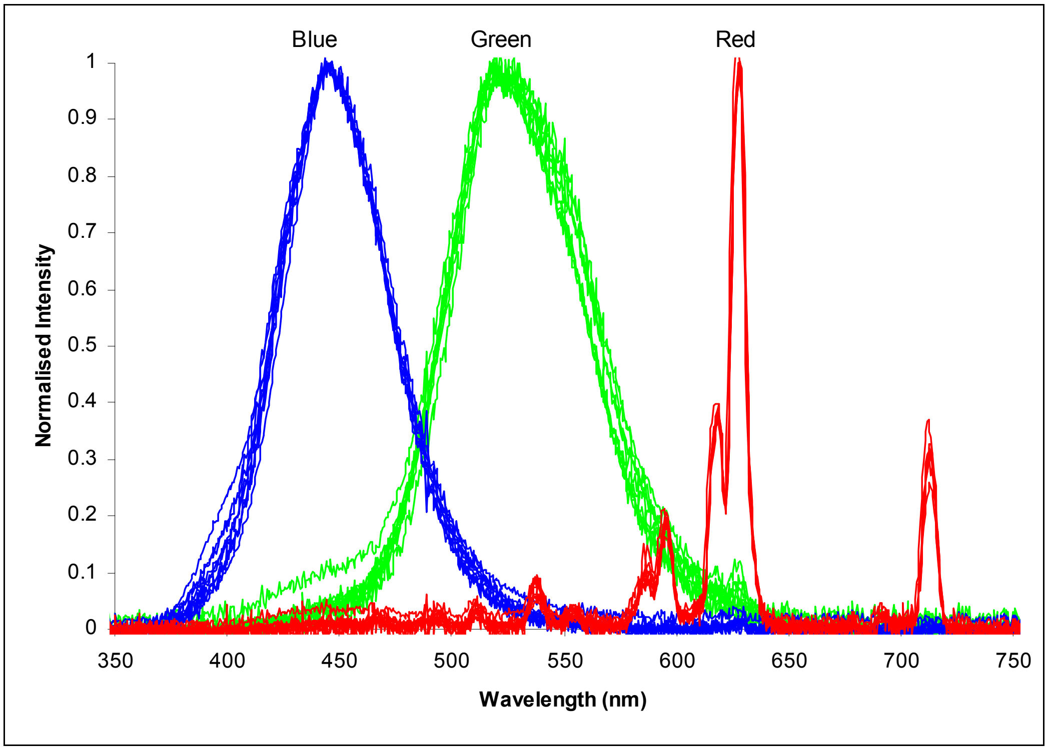


Figure 2: Overlaid spectral output of 11 different CRT monitors.

2.1.2 PHOSPHOR TIME RESPONSE

The phosphor intensity vs. time response of each of the three CRT phosphors was measured using an IPL10503DAL photodiode from Integrated Photomatrix Limited (Dorchester, UK)[8]. The results of this measurement for each of the three colour phosphors are shown in Figure 3. Again, blue and green have a very similar result. In contrast, the red phosphor has a much longer decay. The linearity of the IPL10503DAL was confirmed by a separate experiment[9].

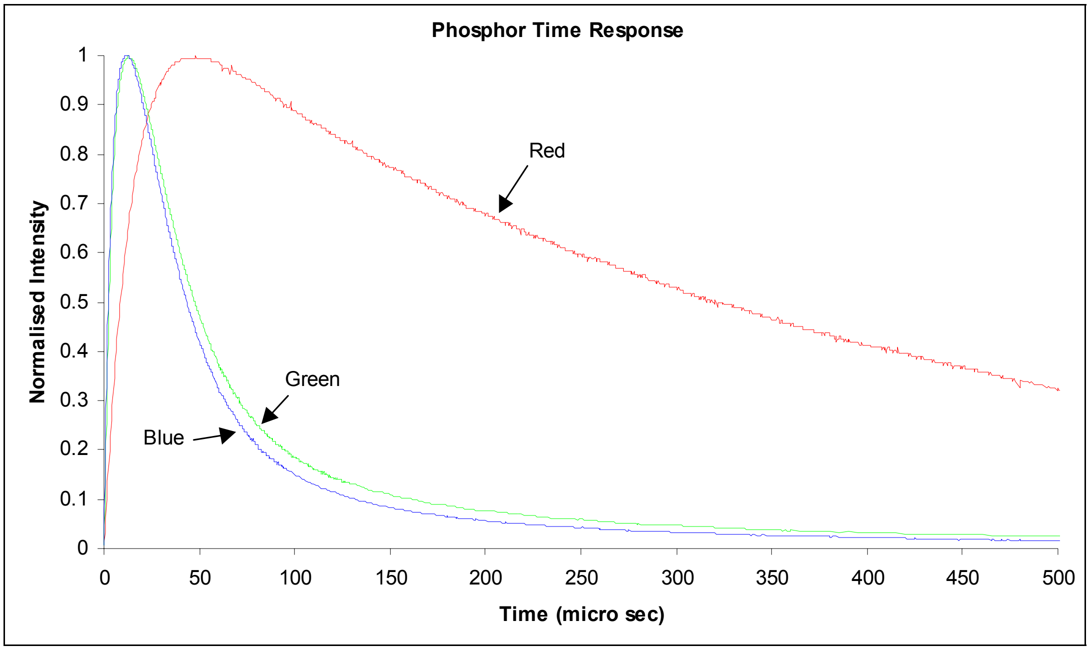


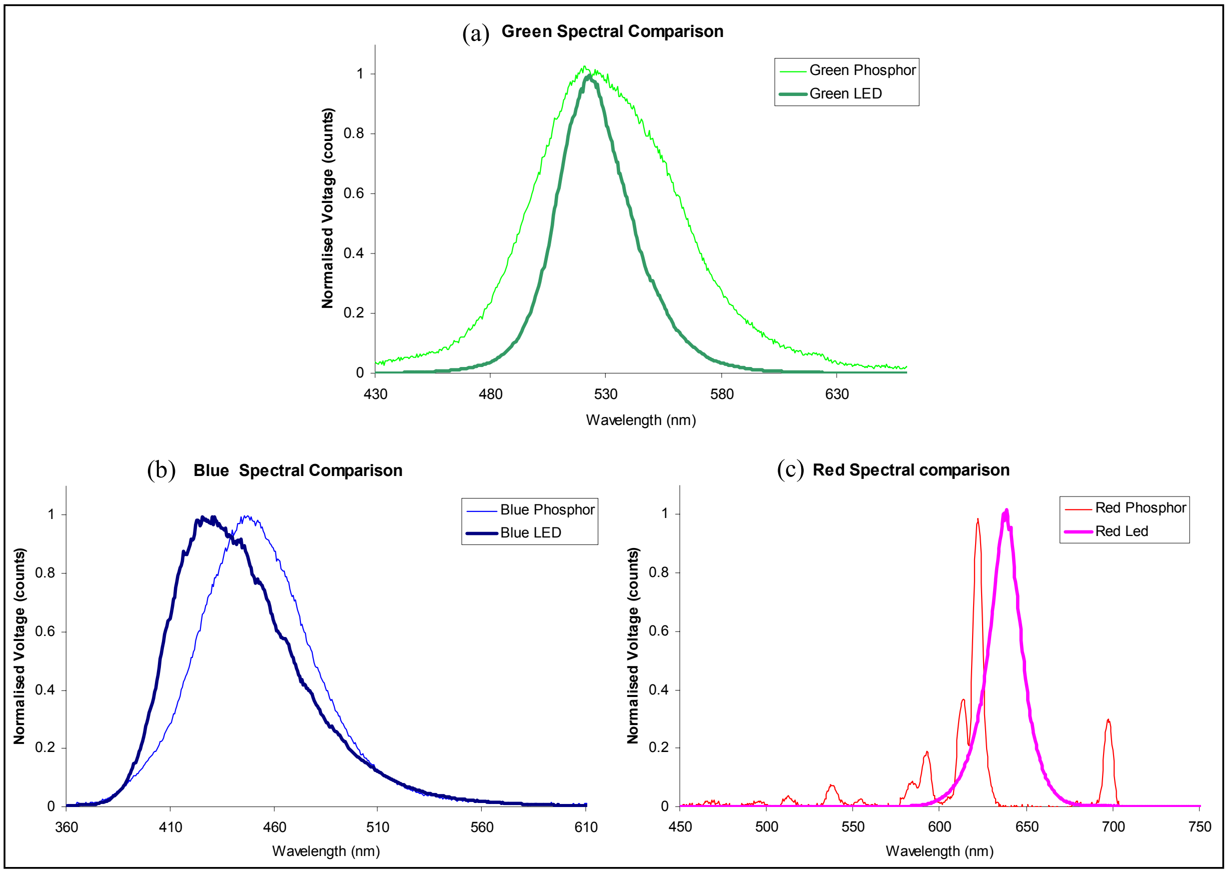
Figure 3: Phosphor intensity vs. time response for the three phosphors of a typical CRT display.

2.1.3 LC SHUTTER TIME/SPECTRAL RESPONSE.

Measuring the transmission vs. time response of the LCS glasses presented a slightly more difficult problem. The optical transmission of a filter (in our case an LC shutter) is normally measured by placing a source on one side of the filter and a detector on the opposite side. The percentage transmission of the filter is given by the percentage reduction in the reading of the detector when the filter is inserted into the optical path. It is possible to determine the optical transmission of the filter at particular spectral frequencies by using a optical source with a particular spectral output.

In our case we were primarily interested in the transmission vs. time response of the LCS glasses at the spectral frequencies output by the individual CRT phosphors. It would have made sense to use the CRT phosphors as the optical source for the transmission measurement, however we were also interested in isolating the time varying transmission response of the LCS shutters and therefore needed an optical source which had a constant optical output versus time. Unfortunately the optical output of the phosphors in a CRT monitor are not constant – the phosphors are modulated by the scanning electron beam – and therefore we could not directly use them as source.

Instead we decided to use LEDs (Light Emitting Diodes) as the optical source. LEDs have a constant optical output, have a fairly narrow spectral output, bright models are available, and they are easy to work with. However, our challenge was to select LEDs whose output was fairly well matched to the spectral output of the CRT phosphors. Figure 4 shows the spectral output of the LEDs that we chose to imitate the CRT phosphors plotted against the CRT phosphor spectral responses. It can be seen in Figure 4 that the blue and green LEDs are a fairly close match to the output of the blue and green phosphors – at least considered close enough for the purposes of this experiment. Unfortunately no single LED is ever going to match the multi-peaked spectral output of the red CRT phosphor so we chose a red LED whose centre frequency was fairly close to the red phosphor's main peak.


(a) Green Spectral Comparison

(b) Blue Spectral Comparison

(c) Red Spectral comparison

Figure 4: The spectral output of the chosen LEDs versus the spectral output of the CRT phosphors for (a) Green, (b) Blue and (c) Red.

The transmission vs. time response of a range of different LCS glasses was then measured using the LEDs chosen above as light sources (individually for red, green and blue) and the photodiode mentioned previously as the detector. A sample result of this measurement on a selected pair of LCS glasses is shown in Figure 5.

The results of Figure 5 show the opaque→transmissive→opaque cycle of a pair of LCS glasses for the selected red, green and blue wavelengths. At 0ms the glasses are in the opaque (extinction) state. At 2.5ms the drive signal of the glasses changes state triggering the glasses to change into the transmissive state. At 22.5ms the drive signal changes again and drives the LCS glasses into the opaque state. This is repeated at the cycle frequency of the drive signal – in this case 60Hz.

A number of things should be observed from Figure 5:

- The results for each of the three colours are not the same – although there are similarities.
- In the opaque state, there is still a measurable amount of transmission – it is not 0% transmission. (This is what we refer to as shutter leakage.)
- In the opaque state, the red transmission is considerably higher than the transmission of the other two colours.
- At the opaque to transmissive transition it can be seen that the glasses switch gradually to the transmissive state – the state change is not immediate.
- The percentage transmission during the transmissive state is not constant. In one case (blue) the transmission increases to a maximum and then decreases. For the other two colours (red and green) the transmissions monotonically increase to different equilibrium points.
- The transmissive to opaque state change is fairly sharp compared to the opaque to transmissive state change.

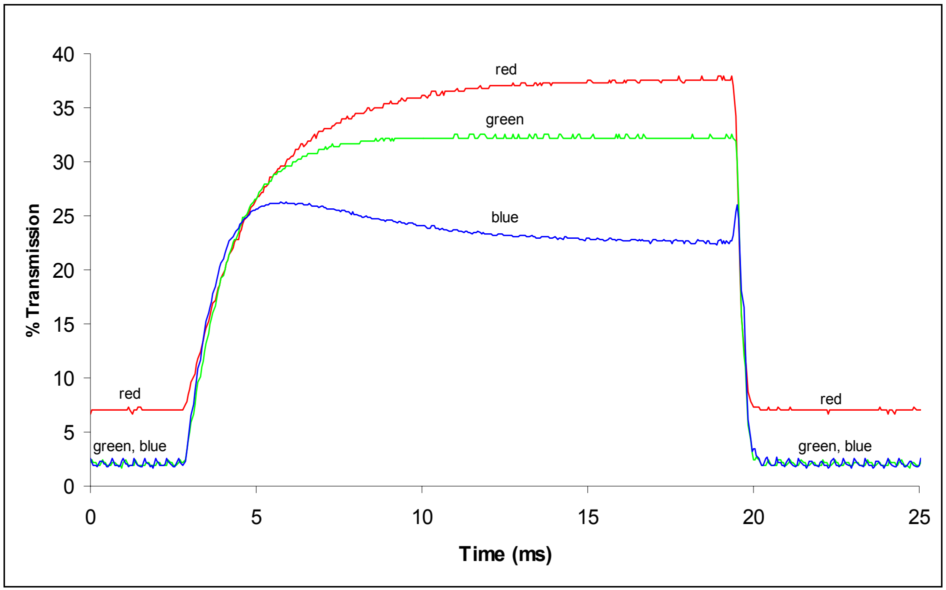


Figure 5: The transmission vs. time response of a selected pair of LCS glasses for the selected red, green and blue wavelengths.

This measurement process was repeated for a range of different pairs of LCS glasses. These results, shown in Figure 6, show a considerable amount of variation. This variation is probably due to differing types of materials used in the manufacture of the various LC shutters sampled. In this test the cycle frequency was 50Hz (except for one set of glasses which had to be cycled at 100Hz). Again the red spectral range exhibits the most leakage during the opaque shutter state.

2.2 THE CROSSTALK MODEL

The three properties described above (phosphor spectral response, phosphor time response, and LC shutter time/spectral response) were combined together in a mathematical model in order to simulate the function of the stereoscopic image crosstalk. The crosstalk model is illustrated in Figure 7.

The top half of Figure 7 shows the shutter response and the phosphor response overlaid on the same time scale. In this case the phosphor response has been exaggerated for illustrative purposes. In real life the phosphor response is considerably narrower. The horizontal axis shows the time for one complete shutter cycle – one image for the left eye and then one image for the right eye – with the shutters switching appropriately. This graph actually indicates the time cycle for the right eye – it can be seen that the shutter goes opaque during the display of the left image and is transmissive during the display of the right eye image. In this case the phosphor response curve is positioned to coincide with a pixel close to the top of the screen and for the left eye image.

The vertical dashed lines on the graph indicate the start and finish of the vertical blanking interval. This is the time in which no picture information is being drawn on the screen. For example, "End of VBI1"[†] coincides with the start (top) of the left image and "Start of VBI2" coincides with the end (bottom) of the left image.

From 18000 μsec on the bottom half of Figure 7 shows the amount of light from a pixel on the left eye image that has leaked through the LC shutter and can be seen by the right eye. This has been calculated by multiplying the shutter response and phosphor response together. Ideally this curve would be zero, however its presence indicates the presence of crosstalk.

[†] VBI = Vertical Blanking Interval

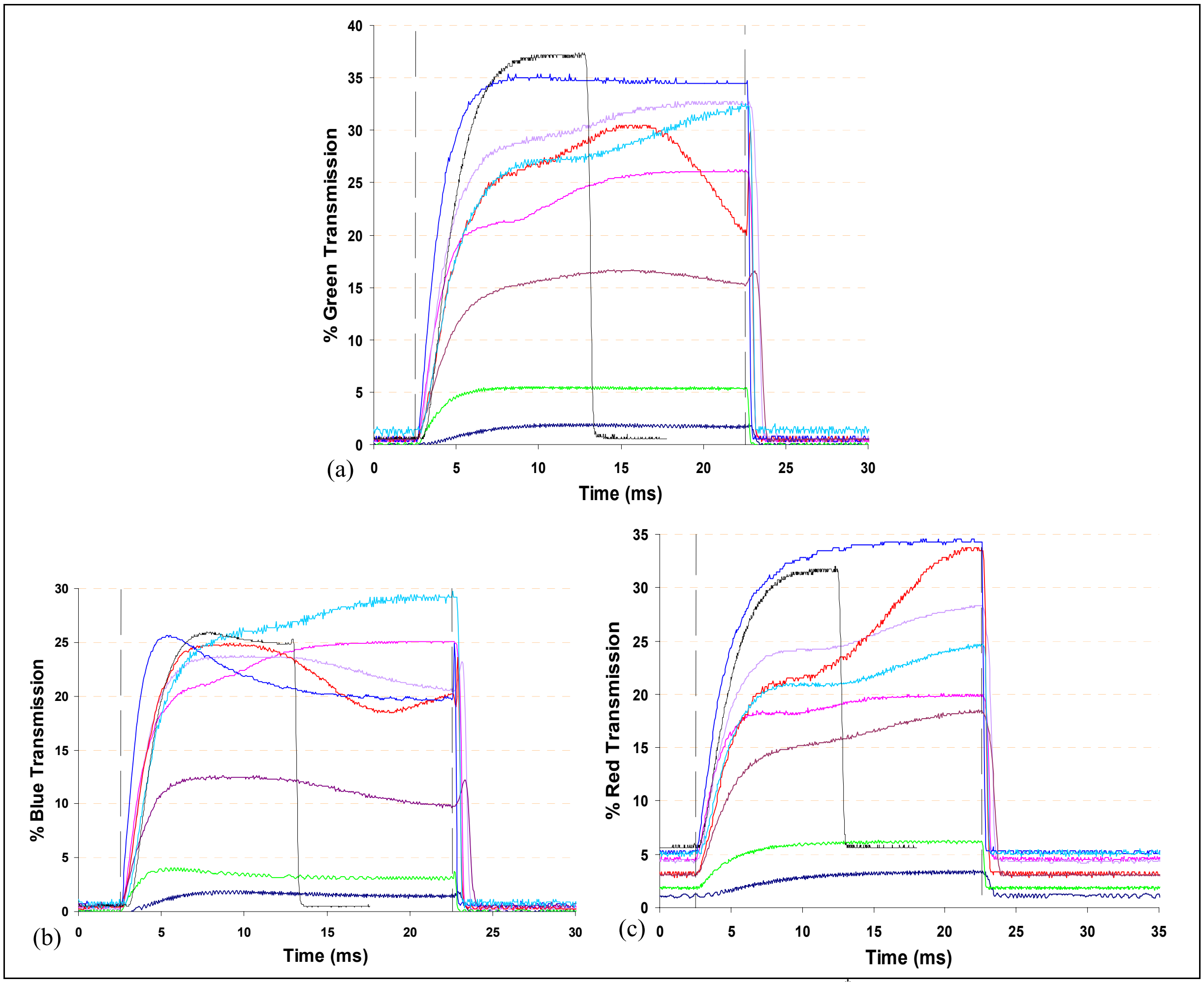


Figure 6: The transmission vs. time response of a selection of different LCS glasses[‡] in the (a) green, (b) blue, and (c) red spectral ranges.

The total amount of crosstalk (for this specific pixel position) is then calculated by integrating the area under the bottom curve.

To determine the contribution of each crosstalk source to total crosstalk, the time integration is divided into two regions, one encompassing the duration of the shutter's transmissive state, and the other encompassing the shutter's occlusion state. The time integration taken while the shutter is in its occlusion state represents the average crosstalk light energy 'leaking' through the 'imperfectly' occluded shutter and is due to shutter leakage. Similarly, the integration taken while the shutter is in its transmissive state, while none of the left image should have been visible, will represent the average crosstalk light energy received due to phosphor afterglow.

[‡] Please note that we have intentionally not listed the manufacturer and model of the various LCS glasses measured. In most cases we have measured only one pair of glasses and hence this may not be representative of all LCS glasses of this model. The basis of this graph is that there can be considerable variation between different LCS glasses.

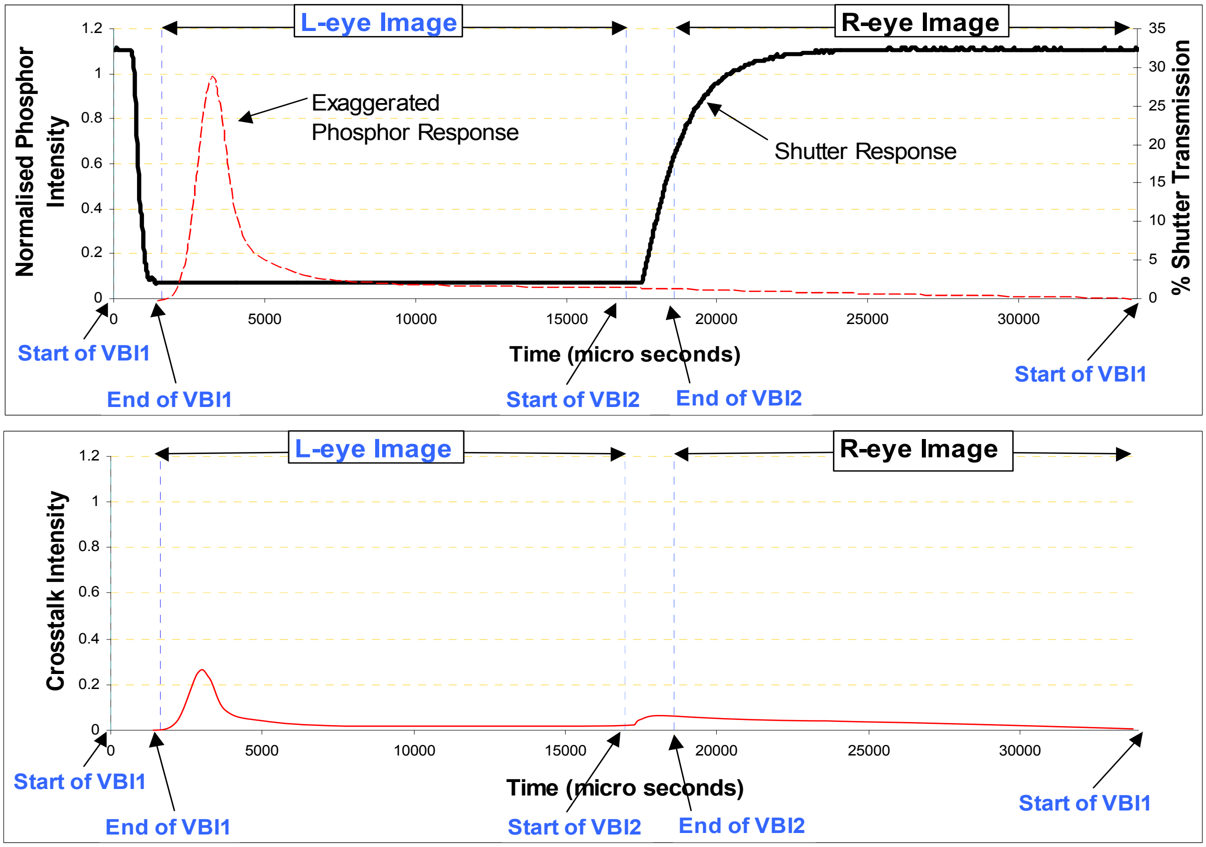


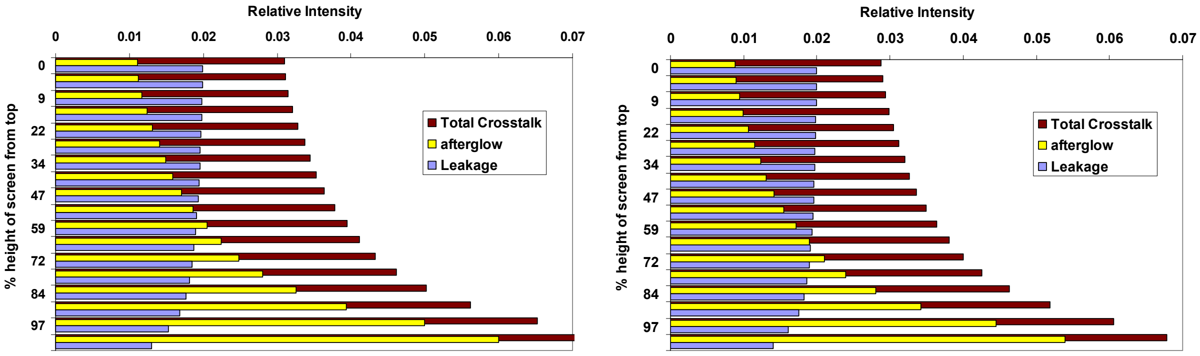
Figure 7: Illustration of the crosstalk model (with exaggerated phosphor response for illustrative purposes). Top: phosphor response and shutter response. Bottom: multiplication of phosphor response by the shutter response to give the amount of crosstalk.

To calculate the crosstalk at another pixel, let's say further down the screen, the above procedure is repeated with the phosphor response delayed in time with respect to the shutter response by the appropriate interval. (This reflects the fact that each pixel on a CRT is excited at a slightly different time. For a typical raster scanning pattern, the cathode ray sweeps horizontal lines down the screen, from the top-left to the bottom-right.) In this iterative fashion, a ghosting profile w.r.t. screen position can be gradually built up.

3. RESULTS

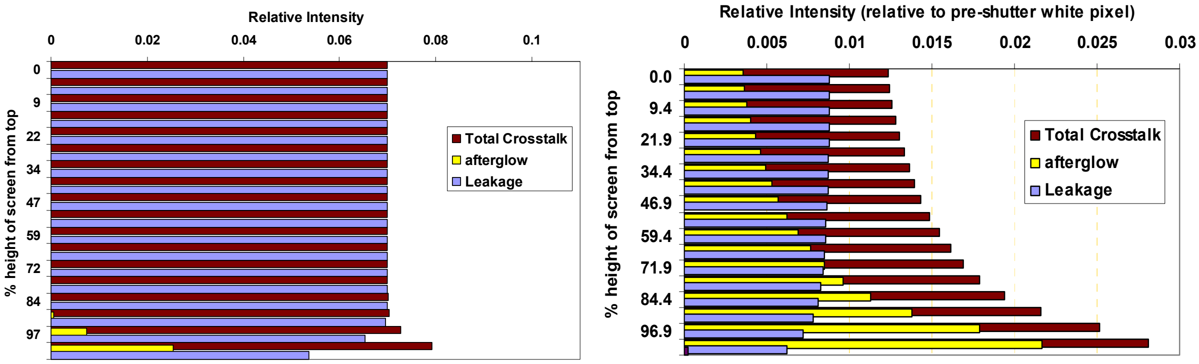
3.1 CROSSTALK MODEL RESULTS

The crosstalk model discussed in Section 2.2 has been prototyped in Excel and uses the input data illustrated in Figures 3 and 5. In this first instance the model has been calculated for a screen refresh rate of 60Hz. The crosstalk model has been run for each of the three colours and also for multiple positions down the screen. The results for each of the three primary colours are shown in Figure 8(a,b,c). The graphs show three parameters: (a) total crosstalk, (b) crosstalk due to shutter leakage, and (c) crosstalk due to phosphor afterglow, plotted versus screen height.



(a) Blue ghosting composition w.r.t. screen height

(b) Green ghosting composition w.r.t. screen height



(c) Red ghosting composition w.r.t. screen height

(d) Avg. RGB ghosting composition w.r.t screen height (scaled with eye response and CRT RGB composition)

Figure 8: Crosstalk source composition versus screen height for: (a) blue, (b) green, (c) red, and (d) average brightness.

The results for blue and green are remarkably similar - at the top of the screen ghosting is mostly due to shutter leakage, and at the bottom of the screen ghosting is mostly due to phosphor afterglow. The blue and green figures also show a monotonic increase in total crosstalk as we move down the screen. The result for red is quite different from blue and green which is probably due to the high level of transmission during the LCS extinction period for red (see Figure 5). We would have expected the amount of red afterglow (in Figure 8c) to be significantly more but this might be an error due to the limited accuracy of our photodetector system at very low light levels. For all graphs of figure 8, the maximum amount of crosstalk is at the bottom of the screen - which agrees with our perceptual assessment of crosstalk and also with Bos[5].

The results for the three colours have then been combined into a single average brightness (luminance) result shown in Figure 8(d) by taking into consideration the eye's spectral response[10] as well as a CRT monitor's usual balance between red, green and blue to obtain white light. If we average the crosstalk due to each of the sources over the whole screen (for the average brightness case), we find that shutter leakage and phosphor afterglow are almost even contributors at 51.1% and 48.8% respectively.

It should be emphasised that these results apply only to the particular system that we have measured (LCS glasses, shutter rate, etc). The results for a different system could be significantly different from these results and would require a new set of data to be input into the crosstalk model.

3.2 VALIDATION

To provide us with a quick check that the results from the crosstalk model were close to correct, we used a digital camera to capture the presence of crosstalk on a time-sequential stereoscopic display. Although the digital camera (a Kodak DC625) is by no means a metric device, it would at least provide us with some level of validation.

Figure 9 shows a photograph taken through the right shutter, with the glasses shuttering, the screen was showing a time sequential image, the right image was set to black and the left image was set to full screen 100% green (the other colours were tested separately). The increase of crosstalk toward the bottom of the screen can be clearly observed, and is in accord with the crosstalk model results shown in Figure 8. Figure 10 shows a 3D plot of the data of Figure 9 and shows the nature of the increase in ghost intensity at the bottom of the screen.

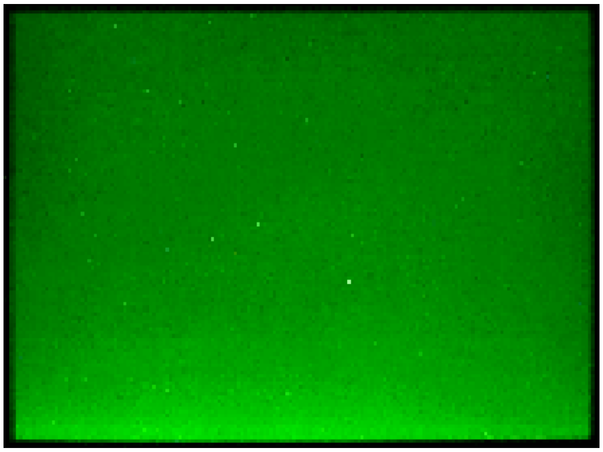


Figure 9: Digital photograph of green ghosting

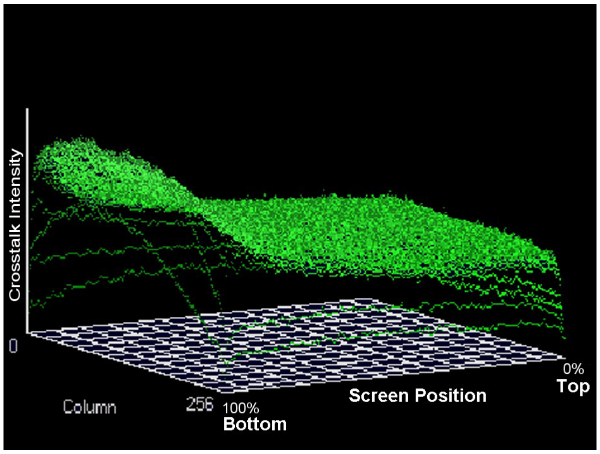
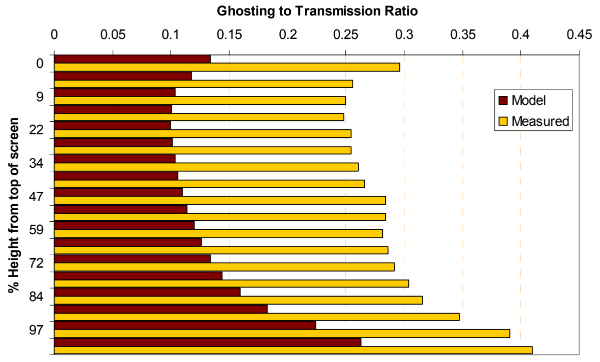


Figure 10: 3D histogram of Figure 9

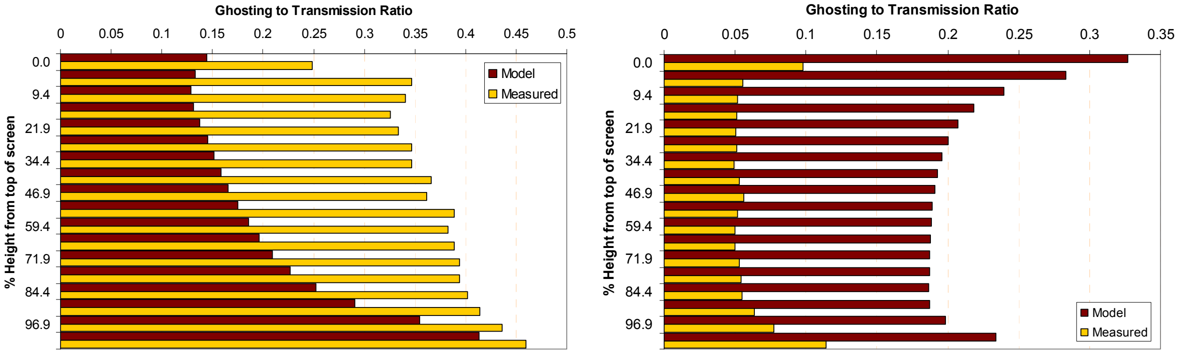
In order to compare the crosstalk model with the digital camera results for total crosstalk, the ghost to (intended) transmission (G/T) Ratio with respect to screen height was calculated. This ratio was used since the camera's absolute light sensitivity was unknown. Figure 11 shows a comparison of (G/T) ratio calculated from the crosstalk model, and that calculated from data extracted from the digital photographs for each of the three primary colours.

The closest match is with the green response. Although there is an offset between the two curves (modelled and measured), the 'shape' of the two curves is remarkably similar. The similarity of the two curves provides some reassurance as to the accuracy of the crosstalk model for the green case. The offset between the two curves may be due to a scaling, exposure or non-linearity issue with the digital camera or may simply represent an error with the crosstalk model.

The results for blue and red (Figure 11b,c) aren't quite as close but the shape is somewhat similar. An offset between the model and the measured is again present.



(a) Green Phosphor



(b) Blue Phosphor (c) Red Phosphor

Figure 11: Ghost to Transmission Ratio Comparison for (a) Green, (b) Blue, and (c) Red.

4. CONCLUSION

This paper has discussed the development of a model for crosstalk/ghosting in time-sequential stereoscopic displays. The model provides insight into the mechanisms by which crosstalk occurs. Preliminary validation of the model indicates that it gives a reasonable prediction of crosstalk, however more work is needed for complete validation.

Some of the limitations of the current crosstalk model are: the method used to measure the LCS transmission response in the red channel may not be accurate (because the LED spectral response does not match the red phosphor response), the CRT phosphor afterglow measurements may not be entirely accurate (the photodetector system that we used has limited accuracy in low light levels), and the photodetector system has a bandwidth which is very close to the expected bandwidth of the phosphor afterglow response (hence we may be missing high frequency information for the phosphor time response).

The advantage of the crosstalk model is that it allows the quick simulation of crosstalk under a variety of conditions and hence may be a useful tool to help find ways to reduce crosstalk in stereoscopic displays.

One immediate observation of this study is that the first thing to consider when attempting to reduce crosstalk is to consider changing the LCS glasses (or at least review the performance of the LCS glasses being used). This study found considerable performance variation between various makes and models of LCS glasses. In contrast, very little performance variation was noted between commonly available CRT monitors – hence little change is likely to be obtained by simply swapping monitors. Monitors with short phosphor persistence may well be available by special order but this was beyond the scope of this particular study.

The crosstalk model in its current form isn't particularly user friendly and could be rewritten to improve this aspect. The crosstalk model could also be extended to simulate the use of stereoscopic polarisation modulator panels (such as available from NuVision and StereoGraphics), and could also be modified to simulate the change in crosstalk that would occur with higher field/frame rates. Using a different phosphor time response data set, the model could also simulate the use of CRT projectors for time-sequential stereoscopic display (CRT projectors have a different phosphor time response and spectral response than most CRT monitors).

We have also considered the effect of some of the other sources of crosstalk (as discussed in the introduction), however a full description of these studies is beyond the scope of this paper. [9]

We hope that the reader has gained a better understanding of the mechanisms of stereoscopic image ghosting/crosstalk from the presentation of this research.

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