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MASTER THESIS WORK

LCD handheld displays characterization by means of the MTF measurement

Beatriz Martínez Navarro

Supervised by Dr. Jaume Escofet and Dr. María Sagrario Millán (EUOOT. UPC)

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LCD handheld displays characterization by means of the MTF measurement.

Beatriz Martínez Navarro
Applied Optics and Image Processing Group. EUOOT. UPC. Terrrassa, Spain

E-mail: beatriz.martinez@citm.upc.edu

Abstract. The MTF of the display devices can be calculated using different methods. Among them, the square-wave and the LSF inputs are the most used. In this work, the MTF of three handheld devices (two tablets and a smart phone) is measured by analysing the PSF, which is obtained by photographing a bright pixel displayed on each device and calculating its Fourier Transform. This method allows obtaining the horizontal and vertical MTFs but also the average MTF of all the 2D FFT directions. The measurement is applied to a grey image and also to red, green and blue images, in order to compare the performance of the displays for different colours. Finally, the results are compared with those obtained with a more common method, as the square-wave.

Keywords: Liquid Crystal Display (LCD), pixel, sub-pixel, Point Spread Function (PSF), Modulation Transfer Function (MTF), square-wave (SW).

1. Introduction

The use of a wide variety of display devices to visualize all kind of images is quickly growing. The large amount of smart phones, tablets, laptops and other display devices allows the visualization of any kind of image, from the pictorial ones to the medical images used in telemedicine. In the last case, and in other scientific or technical applications, the quality of the visualized images can be critical for the correct interpretation of the information that they contain. Moreover, the image quality performed by the capturing system can be dramatically affected by the displaying device if the last is not at the same level of quality as the imaging device. Although handheld devices (smart phones and tablets) differ significantly in size from bigger displays (laptops and workstation displays), the rapid advances in technology deserves displaying systems with progressively smaller pixels. That is why the spatial resolution of handheld displays has increased significantly in the last years; this is the case, for example, of the so-called “Retina display” technology, which achieves a resolution that doubles that of the previous systems used in tablets. In consequence, as previous works conclude [1], handheld displays can have good image quality characteristics compared to medical workstation displays, in terms of spatial resolution, noise and reflectance. Although image quality characteristics of several workstation displays have been extensively assessed, the rich variety of handheld display devices has not yet been fully characterized.

The characterization of display devices includes the measurement of luminance, contrast, resolution, noise and maximum visual angle, among others [2]. The evaluation of spatial resolution by calculating the display MTF is one of the most relevant and several methods can be carried out in order to measure it. Therefore, the MTF can be measured by displaying an edge stimulus, a line stimulus (LSF), white noise stimulus or square-waves of different frequencies. These methods have been applied in previous works by other authors in order to characterize the resolution of CRT, LCD and OLED displays; some of these works compare different methods in terms of data acquisition and analysis time consuming [3, 4], or in terms of their dependence on other variables as luminance or noise [4, 5]. Besides, other works are based on applying a unique method to characterize different display devices [1, 5, 6, 7]. From these references, it can be concluded that the different systems used to calculate the MTF give similar results and that the most used are the square-wave and the LSF methods, as they are the most simple and the less time consuming.

As the displayed stimulus used to calculate the MTF (edge, line and bar-patterns) are one dimensional and the LCD technology has a complex pixel structure which is very non-uniform and non-isotropic, both horizontal and vertical MTF are always measured, obtaining different results for each direction, depending on the pixel and sub-pixel structure. Moreover, the displayed stimuli are typically grey, having a balanced luminance of the three R, G and B sub-pixels of a pixel. Therefore, the previous studies present the results of measuring the vertical and horizontal MTF of grey inputs. This kind of information can be useful to compare different devices, but it does not provide enough information to evaluate the resolution when displaying edges in directions different than horizontal or vertical and when displaying colour images. The results under these conditions could be different due to the typical pixel and sub-pixel structure.

Taking into account that most of the displayed images in real applications are usually colour images containing edges and structures in all directions, in this paper the MTF's of three handheld displays are measured for the vertical and the horizontal directions of grey stimulus, but also for the average of all directions and for red, green and blue stimuli. The scope is to analyse the possibility of obtaining these measurements by applying two different methods and to analyse the results in order to determine the differences in resolution when displaying images with slanted colour edges.

One of the methods applied in this work is a variation of the LSF method; instead of displaying a line of pixels over a uniform background, only one pixel with a higher luminosity than the background is used in order to obtain the PSF of the display. From this luminous point, the vertical and horizontal sections of the PSF (rows and columns of its image) can be used to provide the respective vertical and horizontal MTF's. The whole 2D MTF can also be measured. Moreover, applying different input values to the three R, G and B sub-pixels, the PSF for different colours other than grey can be also used to measure the MTF under these conditions. The results obtained with this method are compared with those derived by the square-wave method. With the last, only the vertical and horizontal MTF's can be obtained, but it can be applied also for bar-patterns of different colours. Both methods are used to characterize the resolution response of three handheld devices: a medium resolution tablet (iPad2), a high-resolution tablet (iPad Retina) and a smartphone (iPhone 4).

2. Materials and methods

2.1. Displays

Three handheld displays have been used to measure their MTF. In order to analyse three different devices with different spatial resolutions and screen sizes, two tablets with different pixel size (iPad 2 and iPad Retina) and a smartphone (iPhone 4) have been chosen. The size, the pixel pitch, the Nyquist frequency and the maximum luminance of each of them are shown in table 1. In order to do the measurements, the brightness has been set at the maximum level (the contrast cannot be adjusted in this kind of devices), and all of them have been situated in his landscape orientation.

Table 1. Resolution and luminance characteristics of the three analysed devices.

	Display Size (pixels)	Pitch (mm)	Nyquist frequency (lp/mm)	Max. Luminance (cd/m^2)
iPad 2	1024x768	0,192	2,6	150
iPad Retina	2048x1536	0,096	5,2	130
iPhone 4	960x640	0,078	6,4	200

2.2. PSF method

The minimum unit of information of a display device is the pixel, which consists of a square area containing three sub-pixels, one red, one green and one blue. For an LCD, the discrete data represented as the input signal is blurred by the pixel structure. The resolution characteristic of LCDs mostly depends on the inherent luminance profile according to one pixel structure. Talking in terms of image formation, the pixel can be considered as the PSF of the display. Then, from the PSF it is possible to calculate the MTF of the system, knowing that the MTF is the modulus of the Fourier Transform of the PSF.

2.2.1. Input images.

In order to obtain the PSF's of the displays, a series of images with a uniform background and a brighter pixel have been generated. For each device, the series of images contain an image with the same grey value for the RGB components (grey image) and three images brightening only de red, the green and the blue components, respectively.

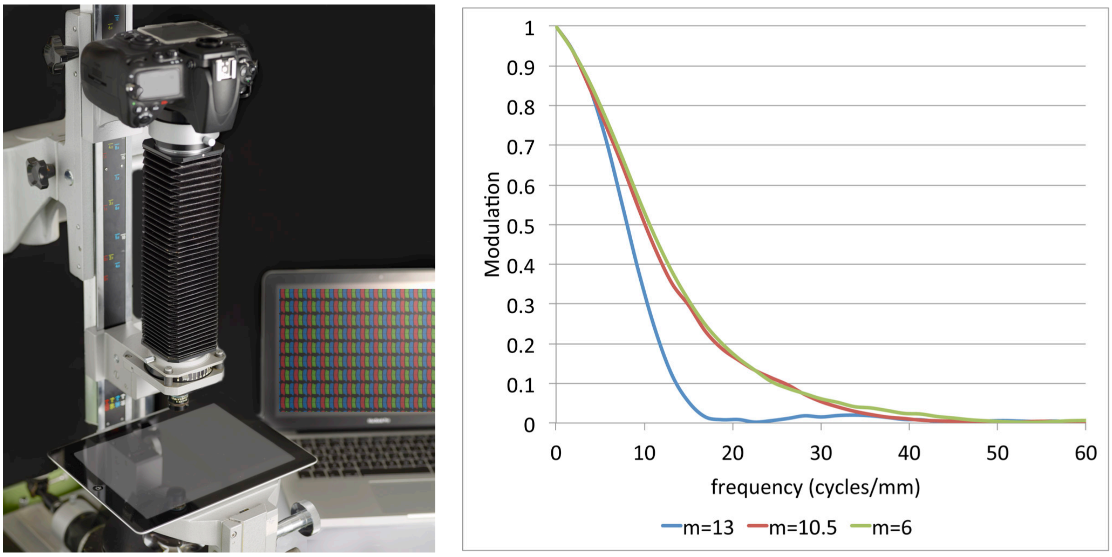
In order to establish the input luminance value applied to the background and to the pixel, it must be taken into account that the luminance response of the displays is not linear and this may cause variations in the MTF measurement. To obtain a linear response in the luminance of the displayed image, the amplitude of luminance between the background and the brighter pixel must be small [1, 3, 4]. The guidelines of the American Association of Physicists in Medicine (AAPM) suggest that the amplitude is 12% of the pixel value contrast for the background. Other works [1] use a pixel value and a background value of the 60% and the 50% DDLs (digital driving levels), respectively. In this work, a grey level of 128 (8 bits) for the background and of 180 (8 bits) for the pixels have been applied, which corresponds to a 70% and a 50% DDLs. Other luminance configurations (with more amplitude) have been used and measured in order to confirm the influence of the luminance response on the MTF.

The final images used to perform the measurements must have a black background and a luminous pixel with small amplitude respect to the background. Therefore, a series of images with a uniform background have been created; they will be also captured and substracted to the pixel images in order to eliminate the background.

2.2.2. Image acquisition.

The input images have been displayed on each device and captured by means of a photomacrography system (figure 1.a). This is the Nikon Multiphot equipment with a Macro Nikor 35mm f/4.5 lens, which is corrected for aberrations at the working magnifications, and the Nikon D700 DSLR camera body attached. The CMOS sensor of the Nikon D700 has a size of 24x36mm, 2832x4256 photoreceptors and a Nyquist frequency of 59 cycles/mm. This system allows to obtain images with magnification from m=5 to m=15 and, therefore, to photograph the display pixels with enough magnification to reproduce their structure accurately. For each device, a different magnification has been set, depending on its spatial resolution, in order to obtain PSF's of similar sizes in the final images; the iPad2 pixel has been reproduced with m=6, the iPad Retina with m=10,5 and the iPhone4 with m=13.

Regarding the lateral magnifications when reproducing the pixels, it has to be taken into account that the Nyquist frequencies of the display devices should not be affected by the MTF of the camera when they are imaged. Using the above-mentioned magnifications, the Nyquist frequencies of the displays are around 0,5 cycles/mm in the obtained images. The modulation of the camera at these frequencies is higher than 0.95, therefore it can be considered that there is no need to correct for the MTF of the camera. Table 2 shows the magnification used for each device and the resultant Nyquist frequencies in the final images and figure 1.b shows the MTFs of the camera at the three working magnifications.



(a) (b)

Figure 1. a) Photomacrography set up used to capture the images of the displayed pixels. The DSLR camera body is tethered to a computer with the suitable capturing software. (b) MTF's of the imaging system at m=6, m=10,5 and m=13.

Table 2. Nyquist frequencies of the three analysed display devices, magnifications used to obtain the images of their pixels and resultant number of sensor pixels occupied by a display pixel.

	Nyquist freq. (lp/mm)	Magnification	Nyquist freq. in the final image (lp/mm)	Sensor pixels occupied by a display pixel
iPad 2	2,6	6	0,43	130
iPad Retina	5,2	10,5	0,5	120
iPhone 4	6,4	13	0,49	120

Concerning the capture conditions, the diaphragm of the Multiphot lens has been set at f/4.5 in order to minimize the diffraction effects. The exposure time has been set to obtain a correct exposure accordingly to the maximum luminance of each display and the working magnification. With this configuration, five captures in RAW format (NEF) of each displayed image have been obtained and have been processed to 8 bit uncompressed TIFF files, without any modification of the input values. The figure 2.b shows the Optoelectronic Conversion Function (OECF) of the camera system, when processing the files as explained above; the luminance response is almost linear and so the displayed luminance curve is not affected by the capture system.
The five images of each pixel have been averaged to minimize the random noise generated by the camera sensor and the same has been done with the five images of the backgrounds. The resultant image of the background has been subtracted to the correspondent image of the pixel in order to obtain an image of the PSF (single pixel) with a black background.

2.2.3. MTF measurement.
The vertical and horizontal sections of the PSF's have been obtained from the luminance plot of the columns and rows that correspond to the horizontal and vertical pitch of the display, respectively. The luminance values of all the pixel columns that correspond to the width of the PSF have been averaged to obtain the vertical section of the PSF and the same for the horizontal section, but averaging the correspondent rows. By calculating the Discrete Fourier Transform of both vertical and horizontal sections of the PSF's, the respective vertical and horizontal MTF's have been obtained.

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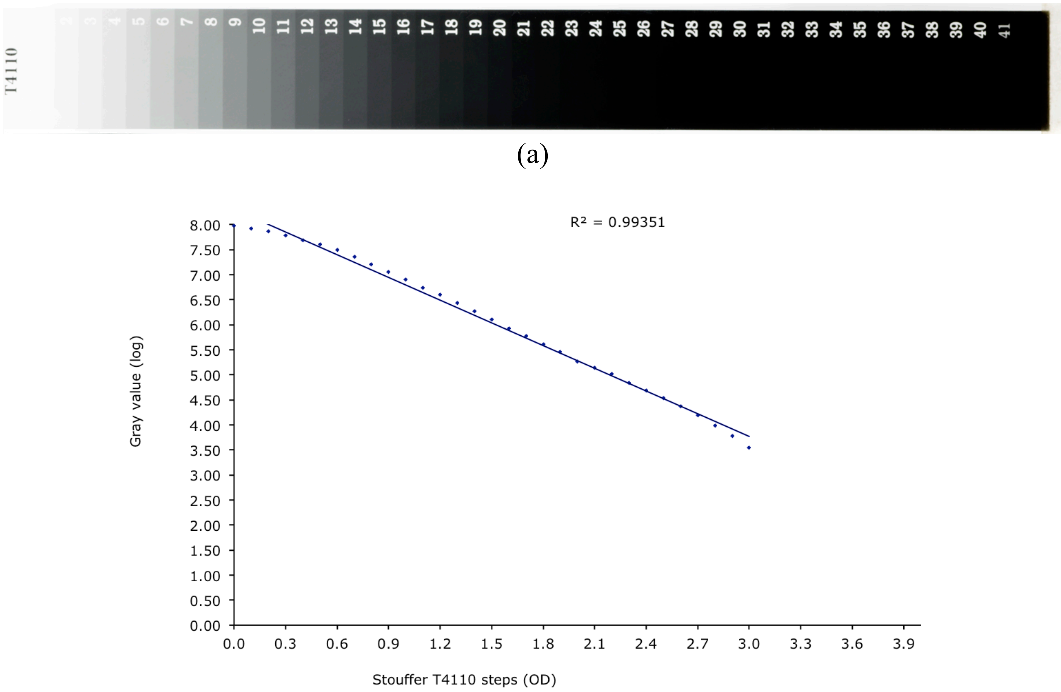
To calculate the average MTF for all directions (called radial MTF in this paper), the 2D Discrete Fourier Transform has been calculated from the PSF image. Then, the modulation values of each frequency at all the represented directions have been averaged and represented in a 1D MTF.



(a) (b)

Figure 2. (a) Test target Stouffer T4110 steps used to obtain the grey levels versus light intensity. (b) Optoelectronic conversion function of the Nikon D700 DSLR camera when applying the processing settings used un this work.

2.3. Square-wave method

2.3.1. Input images.

A series of eight images have been generated, each one containing eight groups of bar-patterns with different frequencies. Each bar-pattern contains five elements with a higher luminance than the background and a width of 1, 2, 3, 4, 5, 6, 7 and 10 pixels for each group, separated by spaces of equal number of pixels in order to obtain the correspondent frequencies (0.5, 0.25, 0.167, 0.125, 0.10, 0.08, 0.07 and 0.05 cycles per pixel, respectively). Two uniform areas with the luminance of the bars and the luminance of the background have been also created in order to calculate the input modulation [4]. This bar-pattern structure has been created for the grey, red, green and blue luminance as well as in vertical and horizontal configurations. The figure 3 shows one of the bar pattern images, with grey luminance and vertical bars, to calculate the horizontal MTF.

In the case of the square-wave method, the amplitude of luminance has been higher than in the PSF method. The difference between the respective bars and background luminance must be high enough to avoid the interference between the respective amplitudes of the fundamental frequency of the square-waves and the pixels of the background. The background has been set to a grey value of 50 (8 bits) and the bars to 128 (8bits). The MTF obtained applying lower amplitude of luminance (50-100) is significantly lower than applying the selected amplitude (50-128).

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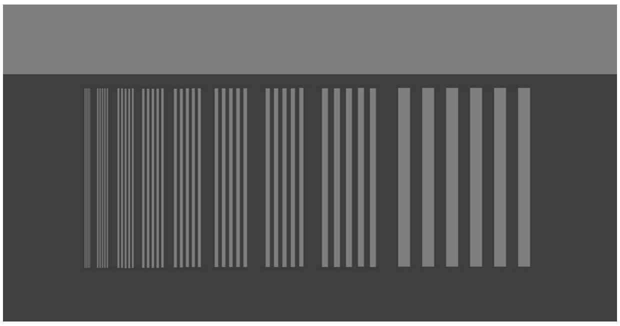

Figure 3. One of the test target images used to calculate the MTF using the square wave method. The eight bars groups correspond to frequencies f_n (n=1-10) of 0.5, 0.25, 0.167, 0.125, 0.10, 0.08, 0.07 and 0.05 cycles per pixel, from left to right.

2.3.2. Image acquisition.

The bar-pattern images have been displayed on the devices and photographed with a Nikon D700 DSLR camera equipped with a Micro Nikkor 105mm f/2.8 objective. The working distance has been adjusted to obtain a lateral magnification of m=0,5 for the iPad 2 and m=1 for the iPad Retina and the iPhone 4. These magnification values have been calculated, for each case, in order to obtain the higher magnification while framing the complete bars groups of lower frequency. The images have been processed with the same settings as in the PSF method.

2.3.3. MTF measurement.

The MTF measurement, in this case, is based on the frequency-by-frequency modulation measurement. It is a more "manual" method and, as only few frequencies are measured, an interpolation process must be done in order to represent a smoother graph.

The fundamental frequency amplitude of input square-wave, S_n (n=1-8), is calculated for each frequency. This is done by calculating the fast Fourier Transform of the theoretical section of the bar patterns that would be imaged if the output of the display were exactly equal to the input. For each bar pattern, a vector has been created with the same length that occupies the section of the correspondent bar pattern in the output image. The values assigned to this vector are, alternatively, those measured on the two uniform luminance areas of the output image (upper zone and background), in order to reconstruct the theoretical input image.

Then, the fundamental frequency amplitude of the output, M_n, is obtained by calculating the discrete fast Fourier Transform of the horizontal or vertical section (depending on the bars orientation) of each bar pattern group and finding the amplitude of the corresponding fundamental frequency (see figure 4). Here, the extraction of exact integer cycles from the obtained square-wave profile is important for precise amplitude determination of the fundamental frequency component [4].

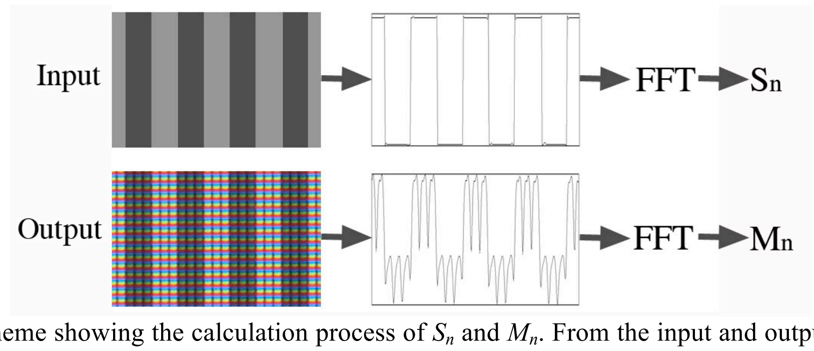

Figure 4. Scheme showing the calculation process of S_n and M_n. From the input and output images of a square-wave with a frequency *n*, the averaged section plots are obtained and the fast Fourier Transform is calculated to extract the amplitude of the fundamental frequency.

The MTF of each frequency has been calculated using the ratio M_n and S_n:

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$$MTF_n = \frac{M_n}{S_n} \quad (1)$$

In the bar-pattern method it has to be taken into account that a square-wave is used instead of a sinusoidal wave, thus the result is overestimated. Therefore, the resultant MTF values should be multiplied by the *sinc* function to correct the overestimations [4]. The MTF as the impulse response of an LCD is defined as:

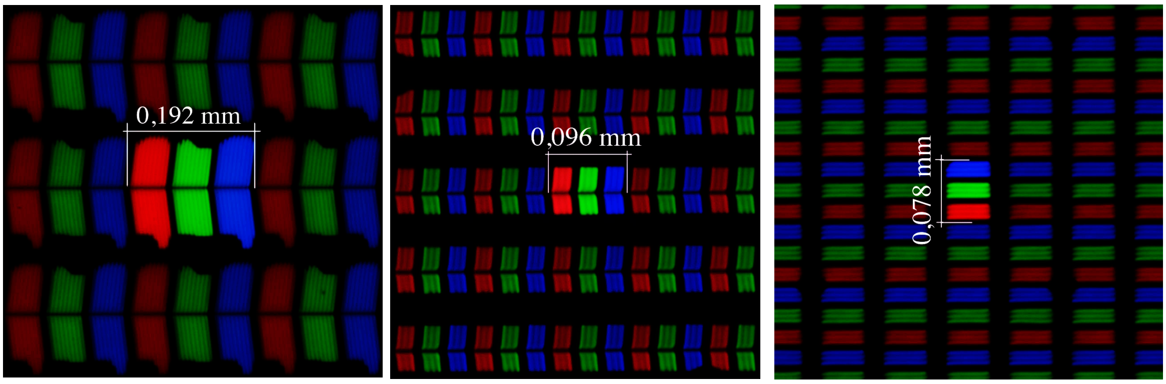
$$MTF_{LCD}(f) = MTF_R(f) \cdot \frac{\sin(\pi \cdot f \cdot p)}{\pi \cdot f \cdot p} \quad (2)$$

Where $MTF_{LCD}(f)$ represents the desired MTF, $MTF_R(f)$ represents the original response obtained by square-wave analysis, f denotes the spatial frequency, and p denotes the pixel pitch.

3. Results

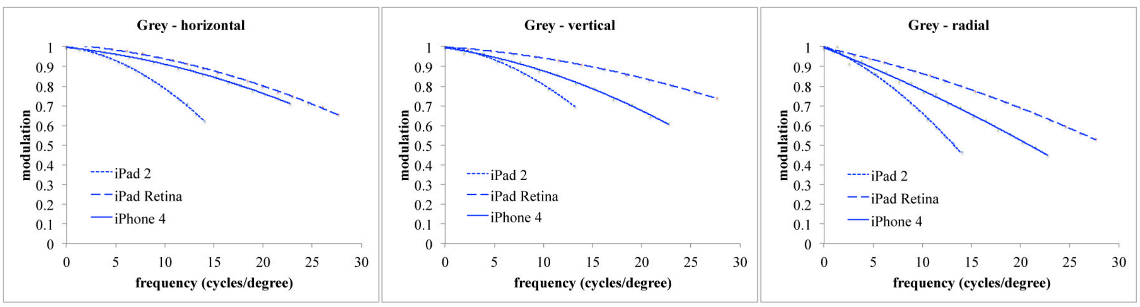
The figure 5 shows the images of the respective PSF of each display device (in the centre of the images), over a grey background with a lower luminance. It can be seen that the sub-pixel structures are different for each device. The two iPad displays are composed by sub-pixels with a slanted shape, especially in the horizontal direction, while the iPhone 4 contains three bars rectangular sub-pixels, with vertical and horizontal edges.

The MTF's of figure 6 have been obtained with the PSF method and show the different performances of the three displays in the horizontal, vertical and radial directions, when displaying a grey image. The frequencies are in cycles/degree because the working distances are different for tablets than for smart phones. As in other references, it has been considered 30 cm for tablets and 20 cm for smart phones. The iPad Retina shows a better modulation in all frequencies (specially for the vertical and radial directions), as well as a higher Nyquist frequency. Is has to be taken into account that the iPhone 4 has a different main orientation of each sub-pixel structure (vertical instead of horizontal) when is used in landscape viewing.



(a) (b) (c)

Figure 5. Pixel images of the three analysed display devices: a) iPad 2, b) iPad Retina and c) iPhone 4.



(a) (b) (c)

Figure 6. The measured (a) horizontal, (b) vertical and (c) radial MTF's of the three analysed display devices in the grey configuration, with the PSF method.

The figure 7 shows all the series of MTF’s obtained for the three displays with the PSF method, in the horizontal, vertical and radial directions, and for the grey, red, green and blue colours. In the horizontal direction the difference between colours is more evident than in the vertical direction, for both iPad’s. In the case of the iPhone, the variability depending on colour is higher in the vertical direction, due to the different sub-pixel orientation. The radial MTF’s show also significant differences for the grey, red, green and blue inputs. The colour with a better performance in almost all cases is green, which is the result of brightening only the central part of the whole pixel area.

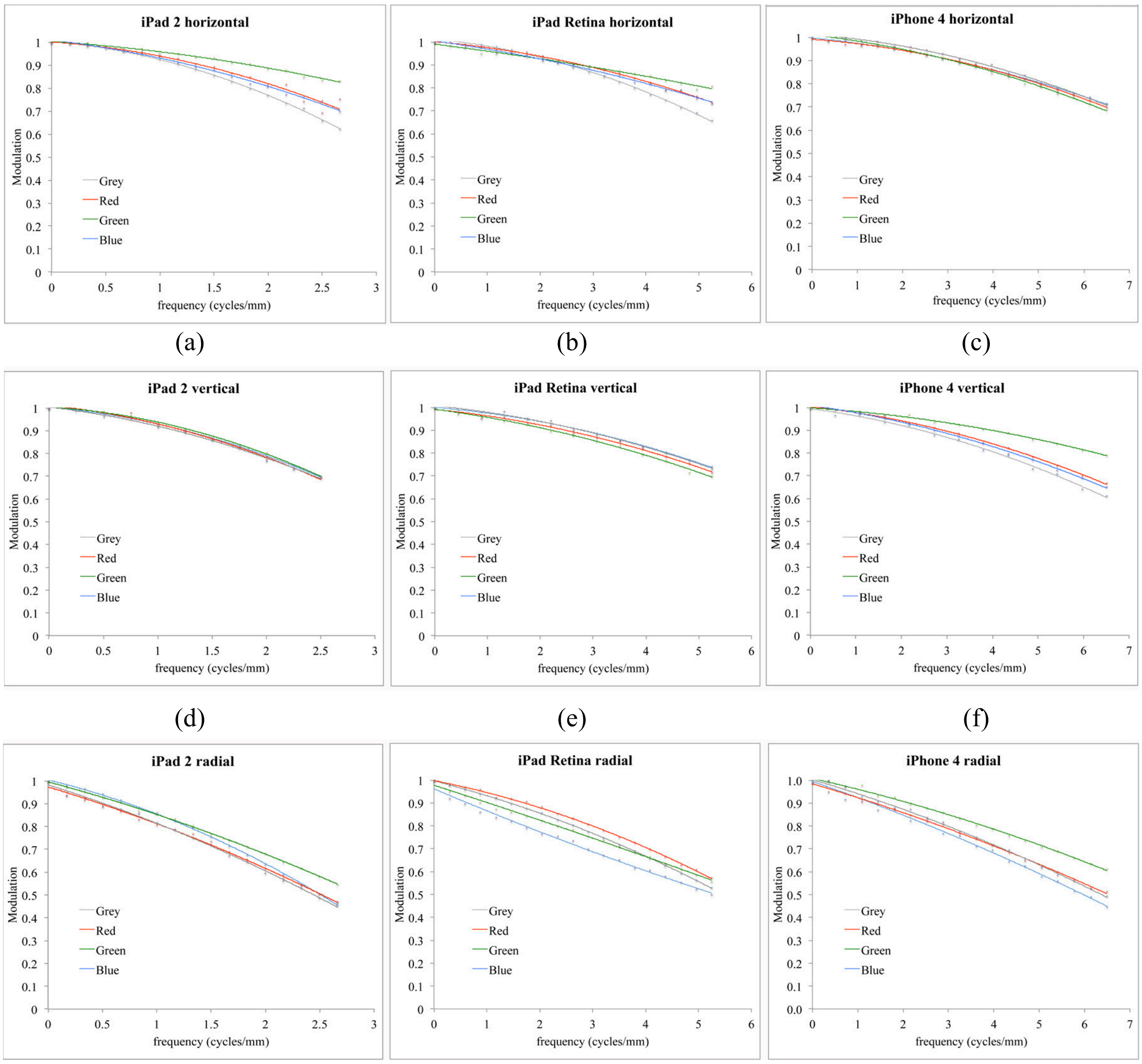


Figure 7. The measured MTF’s, with the PSF method, of the grey, red, green and blue pixels, for the vertical ((a),(b),(c)), horizontal ((d),(e),(f)) and radial directions ((g),(h),(i)).

The figure 8 contains the comparison of the MTF’s obtained by the two methods (PSF and square-wave), for the grey and green colours and for the vertical and horizontal directions. In the case of the iPad 2, all the results are very similar; in this case, the images of the bar-patterns show clearly the structure of the pixels. On the other hand, the MTF’s of the iPad Retina are different when measuring the grey pixels, being the modulation obtained with the square-wave method lower than with the PSF method, while the results for the grey images are very similar. Finally, the MTF’s of the iPhone 4 are lower when calculated with the square-wave method, especially for the vertical direction. It has to be taken into account, that the bar-pattern images displayed on this device do not show clearly the pixel structure.

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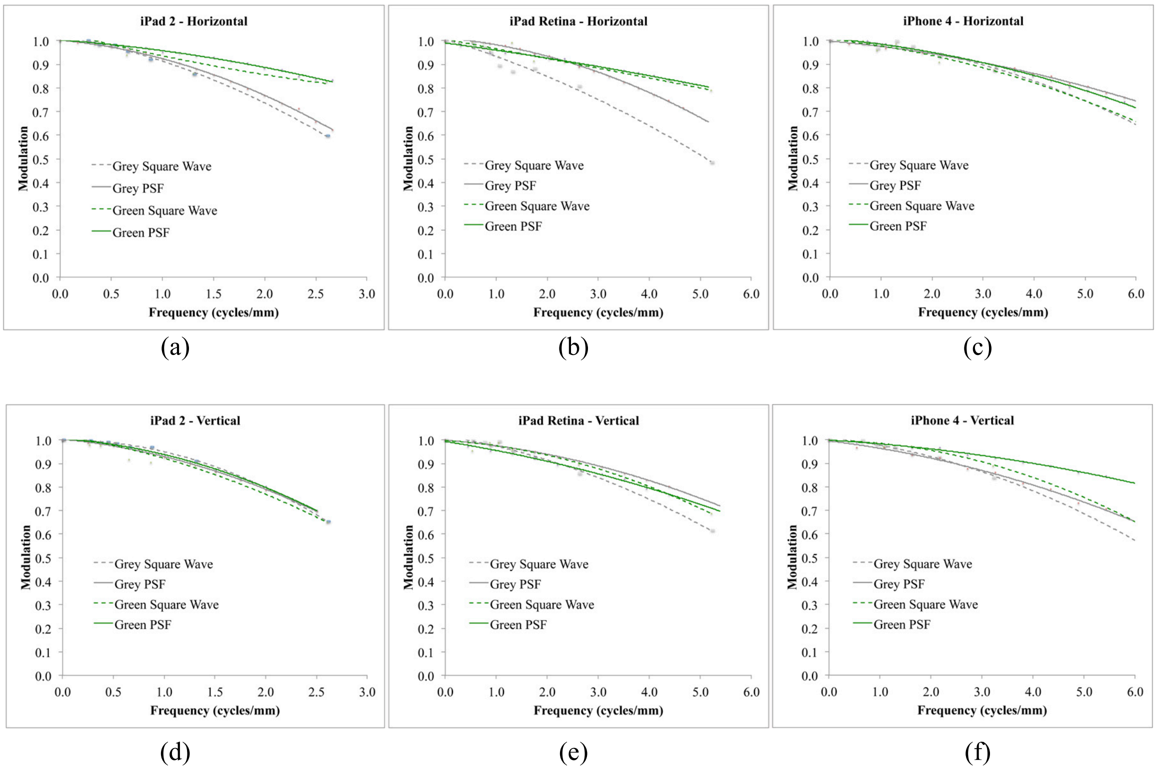

Figure 8. Comparison between the MTFs obtained with the PSF method and the square-wave method, for the grey and green images, and for the horizontal and vertical direction.

4. Discussion

The results show that the use of two different methods give place to similar results when measuring the MTF for cases in which the pixel structure is not relevant; this is the case of the direction parallel to the sub-pixel distribution (vertical direction in the case of tablets and horizontal direction in the case of smart phones) and the display of a colour input, where only one sub-pixel is activated. But when the MTF is measured in the direction perpendicular to the sub-pixel distribution, the pixel structure becomes critical and the different methods give different results, depending on the structure information contained in the analysed images. In this context, the MTF’s obtained with the square-wave method are lower than with the PSF method and the PSF method has a more stable behaviour.

Regarding the results obtained with the PSF method, the comparison between the three analysed devices show that the iPad Retina has a better MTF than the other two when considering the observation distances and measuring the frequency in cycles per degree. Nevertheless, the comparison should be done for the different directions in order to obtain enough information because the MTF has a significant dependence on the measuring direction, related with the pixel structure and the sub-pixel distribution. The differences between vertical and horizontal directions are big enough to consider them separately and the results obtained for the radial calculation (average of all directions) show that the modulation has an important decrease when displaying edges in directions different than horizontal and vertical. For some kind of applications, the radial information can be relevant when characterizing display devices.

Finally, the dependence of the MTF on colour is also remarkable, especially when measuring it in the horizontal direction (vertical for the smart phone). The results for green inputs are in general better than for the other colours, while the blue input has a slightly worse performance.

5. Conclusions

The MTF of display devices can be calculated by different methods, which are based on image acquisition of different displayed outputs. Depending on the method, the displayed output has different characteristics and the displaying and capture conditions must be different. For each method, aspects as the amplitude of luminance of the displayed image, the magnification of the image, the MTF of the camera system and the image processing can affect to the result in a

different manner and must be evaluated and defined before performing the measurements. In the case of the two methods applied in this study, the amplitude of luminance affects the MTF in different ways and the needed magnifications are quite different. These conditions lead to results that are more or less consistent depending on the measuring conditions (direction, colour, pixel pitch, etc.).
Comparing the possibilities of both methods, the PSF method allows calculating the MTF in directions different than horizontal and vertical, as well as averaging all the 2D directions of the PSF. Therefore, the analysis capability of this method is wider. Moreover, the influence of pixel and sub-pixel structure can be analysed with more precision. The drawback of this method is the difficulty of obtaining images with enough quality under the required magnification conditions.
Finally, it has to be taken into account that the image capturing system and the processing settings must be well characterized in order to evaluate and minimize their influence on the MTF results. Further works should be carried out in this field in order to determine if some of the obtained results, as the high MTF's of the green images, are due only to the displays characteristics or depend also on the image capturing process. Effects caused by the different performance of the camera system when focusing different wavelengths or those related with the demosaicing algorithms should be analysed.

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