

A Simple Method for the Measurement of Modulation Transfer Functions of Displays

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Abstract

Accurate measurements of modulation transfer functions (MTFs) of image displays are often necessary for objective quality assessments but are difficult to carry out due to the need for specialized apparatus. In this work, the modulation transfer function of a cathode ray tube (CRT) device is determined by using a monochrome still digital camera of medium resolution. Firstly, a number of computer generated sine wave images of discrete spatial frequencies and constant modulation are displayed and photographed from a close distance. Fourier techniques are employed to extract the amplitude of the display signal form the resulting noisy macroimages. Secondly, measurements are carried out by displaying artificial step-edges and applying the ISO 12233 Slanted-edge Spatial Frequency Response plug-in for automatic edge analysis. The display MTF, in both cases, is extracted from the closed-loop system MTF. The standard test conditions are described, results are compared and advantages and limitations of this approach are discussed.

Introduction

Because of the fundamental nature of this investigation, many available digital cameras are not suitable due to significant and often highly non-linear signal modification methods. These are applied, either in the camera hardware, or imposed by the driving software to improve the subjective impression of the image.[1,2] Experimental work was undertaken here by employing the Kodak DCS420m monochrome digital camera. At its nominal speed of ISO 200, the DCS420m does not apply any major changes to the input signal,[3] apart from tonal correction which is reversible. Image enhancement, such as edge sharpening or noise reduction, are optional parameters in Twain 32 driving software (and were not selected during this experiment), which was used to download the image files from the camera to the host computer.

Only the monochrome MTFs were evaluated in this study, for both the horizontal and the vertical display orientations. Measurements were carried out only for the central area of the display.

Apparatus

The Camera System

The Kodak DCS420m operates with a conventional 35mm SLR camera body and a CCD array of 1524 by 1024 pixels, with 9.0µm square pixel dimensions. The fill factor of the elements is not specified, but a typical value is near 90%,[4] resulting in an aperture size of 8.54µm. The camera, which was always set to its nominal speed of ISO 200, acquires images at 12 bits tonal resolution. The input signal is transfer corrected and down-sampled to 8 bits for output.

The DCS420m body was equipped with an AF Macro Nikkor 60mm f/2.8D lens. The effective focal length of the lens with the size of the DCS420m imaging sensor is 2.6 times the quoted focal length,[5] being approximately 156mm. Only the central 50% of the capturing frame was used in the measurements to reduce distortions within the recording frame introduced by any array spatial inconsistencies, lens response variations, uneven lighting, etc.[6,7] Automatic spot focusing, providing consistent optimum focus in the central area of the frame, and manual exposure modes were employed in the recording of the data, unless stated otherwise. The same camera, lens and settings were used throughout this work. Accordingly the performance of all the components of the acquisition system were evaluated in combination. The device was always mounted on a tripod, with the optical axis being orthogonal to the plane of the target and operating in self-timer mode to minimize image distortions caused by camera shake.

The transfer function of the DCS420m was determined by capturing a Kodak Q-13 greyscale test target, evenly illuminated by two standard 200W photographic grade tungsten bulbs. Correct exposure here, and for every reflection target photographed in later stages, was determined from an 18% greycard. Even illumination was assured by using the in-built spot meter of the camera and measuring 12 equi-spaced points within the frame. The transfer characteristics of the camera were measured from +1 to –1 stops, at 1/3 of a stop intervals.

The CRT Display System

The display system consisted of a NEC MultiSync P750 17 inch CRT, driven by a Matrox Graphics MGA Millenium card in a host IBM compatible PC. The CRT has a 0.25mm mask pitch, (i.e. distance between likecoloured phosphors - manufacturers data) in a slot mask arrangement, where the red, green and blue phosphors are grouped into separate bundles of three, in a vertical alignment, and appear elliptical in shape.[8] The graphics card was con-figured to display 24 bit colour at an addressable resolution of 1024 by 768 pixels and a refresh frequency of 75 Hz.

Before commencing any experimentation, the display system was degaussed and allowed to warm up for a period of at least one hour.[9] All display measurements were carried out in a darkened room. Geometric evaluation (focus, convergence, position, size) was performed by adjusting the appropriate controls of the CRT and with the aid of an image magnifier. The Nokia Monitor Test[10] was imple-mented for the purpose. After adjustments, the active display area occupied 306mm horizontally and 230mm vertically on the CRT faceplate. These dimensions coincided with the factory settings and gave an average of 3.35 pixels per mm horizontally by 3.34 pixels per mm vertically. The colour temperature was set to 6500K using the monitor control of the red, green and blue channel gain and a calibrated Minolta hand-held colorimeter. The brightness (offset) and contrast (gain) of the system were carefully adjusted subjectively, using one very low luminance and one very high luminance targets, both including co-centric rectangles of one pixel value difference.[11,12] The aim was to produce the maximum contrast range with the darkest possible point and with the minimum loss in the available luminance levels. Brightness and contrast was later slightly tuned so that the monochrome display transfer function would approximate a power function with gamma equal to 2.5, offset equal to 0 and gain equal to 1.0.[13]

The monochrome transfer function of the system was measured by displaying, via a C custom-made program, monochrome patches in 15 pixel value intervals between 0 and 255 and using the Minolta meter. The patches covered 50% of the active display area while the surrounding area was set to the opposite pixel value, to ensure equal loading of the system at all measured levels.[14]

Measurements Methods

It is widely known that the determination of the MTF often depends of the method of measurement due to non-linearities.[15,16] The MTF of the display system was evaluated using two different methods: i) the sine wave method and ii) the ISO 12233 Slanted Edge method.[17] The MTF of the acquisition system, was also determined using the same methods and the results were each time removed from the overall system MTF in the usual manner to yield the MTF of the display.

Sine Wave Method

This method involved the display of artificial test images, 256 pixels square, with sinusoidal varying intensity, generated by[18]:

$$I(x) = a + b\sin(\pi\omega x) \tag{1}$$

where $I(x)$ is the pixel value at an horizontal displacement from the origin of x pixels, a is the average pixel value, b is the amplitude and ω is the spatial frequency. b/a denotes the modulation of the input signal. Spatial frequencies of 0.04, 0.05, 0.08, 0.16, 0.19, 0.22, 0.25, 0.29, 0.32, 0.38, 0.44 and 0.50 cycles per display pixel were used with two different modulations of 0.20 and 0.50, at a mean pixel value of 128.

The camera was placed very close to the CRT, with its optical axis exactly orthogonal and centered on the faceplate within one display phosphor precision. The camera lens was covered with a black hood to reduce flare and was set to an aperture of f/11. Correct exposure was identified by photographing a slightly de-focused grey patch (to blur the grid and phosphors structure) with a luminance of 18% of the peak white. Images were captured at 1/3 of a stop intervals and the resulting mean pixel values were matched to these obtained by photographing the 18% greycard. Due to phosphor persistency characteristics the exposure varied constantly between ± 1 and 1/3 stops from the average.

Each sinusoidal test target was displayed in the centre of the CRT while the remainder of the active display area was set to 18% of the display luminance. This grey background represents an average of all displayed images. The targets were displayed at two orientations, at right angles to each other. Five successive frames were captured for each target and each orientation. To avoid data clipping, targets with modulation 0.20 were underexposed by 1/3 of a stop whereas 2/3 of a stop underexposure was given to targets with modulation 0.50. Images were inspected for correct focus and accurate display-camera alignment before they were saved as TIF uncompressed image files on the host computer. Spatial calibration was achieved by photographing a millimeter scale placd in contact with the CRT faceplate. Each camera pixel captured an area of 0.0122mm on the faceplate which with the mask pitch of 0.25mm gave a resolution of more than 20 camera pixels per display pitch. An example of the frame employed in the measurements is illustrated in Figure 1.

The digital images were processed as follows: Mean pixel values perpendicular to the direction of propagation were obtained. In this way the display noise effects were minimized in a similar fashion to integrating with a thin long slit. The careful alignment of the camera as well as the high magnification allowed this thin long slit simulation without introducing errors, even at high spatial frequencies.[19] The resulting one-dimensional traces were then converted into linear units using look-up-tables (LUT) representing the appropriate transfer function of the acquisition system and that of the display.

Identifying the response of the system was not straight-forward because large amplitude fluctuations relative to the sinewave signal at the input frequency were present on the traces. This non-linear noise is due do the discrete and periodical structure of the CRT phosphor and shadow mask arrangement (see Figure 1), which is well resolved when the screen is photographed at such a high magnification. In Fourier space it appears as a set of peaks at discrete frequencies, beyond the estimated Nyquist frequency of the display system.

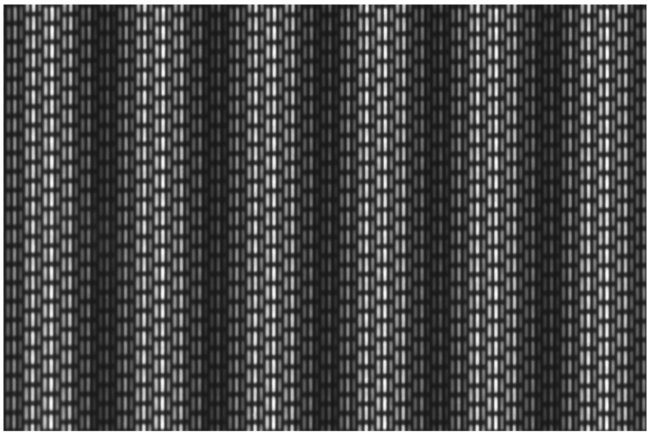

Figure 1. An imaged test target on the CRT.

Low-pass filtering the one-dimensional traces removed these higher frequency components. Figure 2 shows an example of a trace before and after low-pass filtering. Low frequency display luminance inconsistencies may introduce some slight distortion to the output signal. For each cycle in the traces, maximum and minimum signal responses were easily identified. Measurements from five traces were averaged to determine the modulation of the display-camera signal for each spatial frequency by [16]:

$$M_{out}(\omega) = \frac{PV_{\max} - PV_{\min}}{PV_{\max} + PV_{\min}} \tag{2}$$

The number of cycles from which the output modulation was determined increased with respect to the spatial frequency, ranging from 5 to 40. This is because the accuracy in the measurements using the sine wave method decreases with spatial frequency due to phase and noise effects.[16] Measurements were limited to 0.44 and 0.38 cycles per CRT pixel, for the horizontal and the vertical display orientations respectively. These values correspond to approximately 88-76% of the Nyquist limit of the display. The MTF of the combined system was determined by the ratio of the output to the input modulation, with respect to the spatial frequency.[18]

To cascade the MTF of the display system from the combined MTF, the frequency response of the acquisition system was evaluated. Measurements were carried out using a manufactured reflection test target,[20] including fifteen sinusoidal patches of known spatial frequency and average modulation of 0.60. Each patch on the target was photographed separately, at both horizontal and vertical orientations. Multiple one-dimensional sinusoidal traces were extracted from each patch and converted into linear reflectance by employing the appropriate camera transfer function LUT. For each spatial frequency the modulation was calculated from Equation 2 and the MTF was determined using the calibrated input modulation provided with the target.

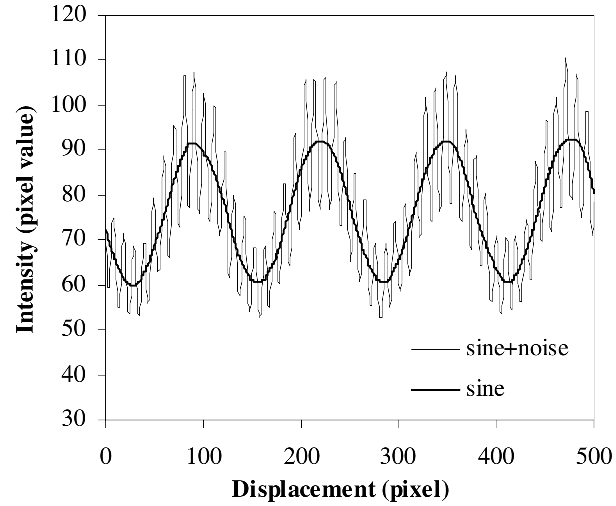

Figure 2. Pre-filtered (sine+noise) and filtered (sine)output signals.

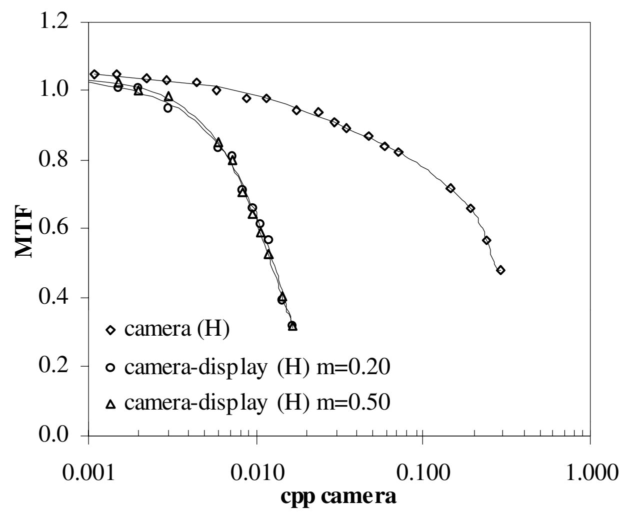

Figure 3. Horizontal (H) MTFs of the display-camera system for two different input modulations (m) 0.20 and 0.50 and MTF of the camera alone, measured with sine waves.

The precise methodology for measuring digital MTFs with the sine method has been described earlier.[16] Phase and noise problems encountered in the determination of the output modulation are not significant at lower spatial frequencies (relative to the camera's sampling frequency) which are of interest here, for cascading the display MTF.

Since the measurements were performed at discrete spatial frequencies, the determination of the display MTF was achieved using third degree polynomial fits, with correlation coefficients, r, always greater than 0.9990. Polynomial as well as exponential curve fit essentially give similar MTF curves to those obtained by linearly interpolating the CRT MTF data.[21] The MTF curves of the combined display-camera system and for the camera system alone, as a function of cycles per camera pixel (cpp), are illustrated in Figure 3, for one orientation. Figure 4 presents cascaded MTFs for both the horizontal and vertical orientations of the display system, in cycles per mm on the CRT faceplate (c/mm CRT).

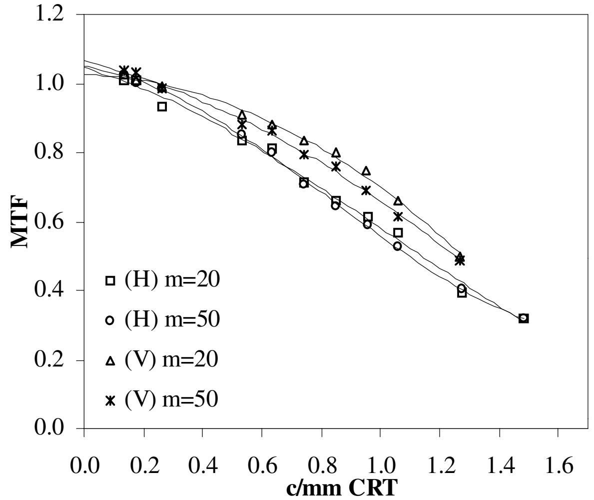

Figure 4. CRT MTFs for two different input modulations (m) 0.20 and 0.50 and for the horizontal (H) and vertical (V) display orientations, measured with sine waves.

The results obtained by this method indicate that once the output signal is corrected for non-linearities, the frequency responses of the system are similar with both 0.20 and 0.50 input modulations. This is a surprise considering the strong dependency of CRT performance on the levels of display luminance. Horizontal and vertical display MTFs differ, but not considerably, with the vertical response being relatively higher. The limit of the resolvable frequencies however is higher for the horizontal than for the vertical display orientation.

The ISO12233 Slanted Edge Method

The ISO 12233 slanted-edge Spatial Frequency Response (SFR) plug-in can be used for the creation of one-dimensional uniformly super-sampled edge profiles and the calculation of the frequency response of digital systems. Details on the method which is based on the traditional edge technique have been published.[22] An account of the computational steps performed by the SFR plug-in is given by Williams,[23] as well as a detailed evaluation of its precision using artificial edges.

Artificial step edges were generated with modulations of 0.50 and 0.70. Edges with lower modulation did not produce the necessary contrast on the CRT for the plug-in to operate correctly. The targets were displayed in the same fashion as the sine wave targets, for both horizontal and vertical display orientations. The camera was placed at approximately 80cm from the CRT faceplate. This distance ensured that more than two pixels were dedicated per CRT mask pitch. Whereas it allowed the necessary blending so that noise introduced by the phosphors and mask structures would not prevent the plug-in operations. The lens aperture was set to f/8 and correct exposure was identified as earlier. The edges were captured with a slope of approximately 15^{o}. That was achieved by bending the camera while its optical axis remained orthogonal to the CRT faceplate. Five consecutive frames were captured for each target, with the edge translated slightly at each shot within an area of 20mm on the faceplate.

A third degree polynomial successfully fitted the combined camera and display inverse transfer function to develop a 256 step LUT, which served as the *Opto-Electronic Conversion Function.*[24] A rectangular *region-of-interest* covering 46 by 280 pixels (in respect to the measuring orientation) was selected form each frame, over which the calculations of the SFR plug-in (version 7.1 in Photoshop) were performed. The vertical to horizontal aspect ratio of the region-of-interest was kept as high as possible to increase the signal-to-noise ratio of the SFR estimates.[23] The measurements covered approximately the same display area as that covered using sine wave targets. For each target and each orientation, average frequency responses were calculated, representing the performance of the combined system.

The average frequency response of the acquisition system to an edge target was evaluated by photographing a quality laser printed stepped edge, at a magnification of 0.05. The edge was printed as a binary digital image file, at 600 dpi. A number of density measurements were taken from the print to ensure that the edge maintained uniform densities all along its length. The low magnification of the system ensured that the frequency content of the target is constant over the desired range.[4] The edge was captured and processed in the same fashion as the display edges, for both horizontal and vertical camera orientations.

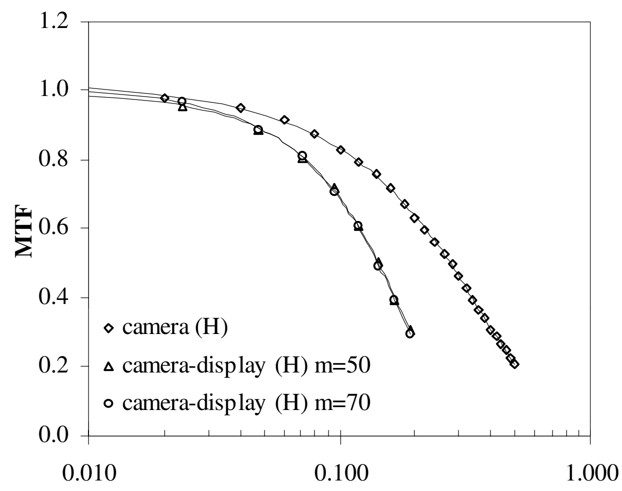

Figure 5. Horizontal (H) MTFs of the display-camera system for two different input modulations (m) 0.50 and 0.70 and MTF of the camera alone, measured with the ISO 12233.

The spatial frequency responses of the combined system and of the camera system alone are presented in Figure 5. The cascaded display MTFs obtained with this method are presented in Figure 6. Vertical display MTFs are shown a little higher than the MTFs for the horizontal display orientation, while both 0.50 and 0.70 input modulations gave the same responses.

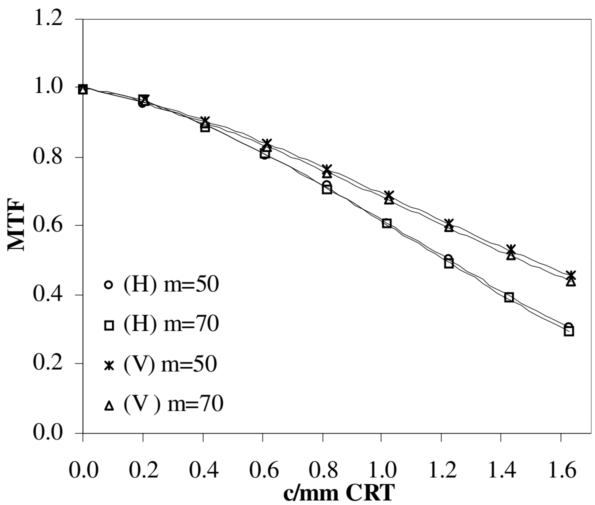

Figure 6. CRT MTFs for two different input modulations (m) 0.50 and 0.70 and for the horizontal (H) and vertical (V) display orientations, measured with the ISO-12233.

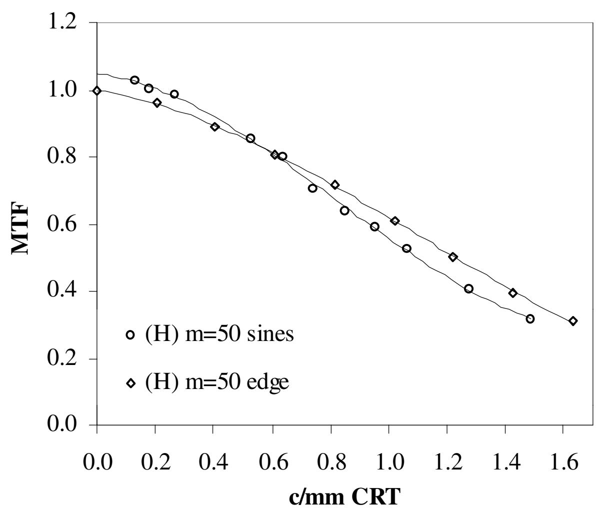

Figure 7. CRT MTFs for the horizontal (H) display orientation determined with the sine wave and the ISO 12233 slanted edge methods.

Discussion

Figures 7 and 8 illustrate MTF curves for both display orientations, measured using the two different techniques. The curves do not show significant differences, with the sine wave method always giving slightly greater low frequency responses and poorer high frequency responses than the slanted edge method.

Generally, it is expected that as a number of variables vary the MTF of the display will vary. The system is not linear, therefore the MTF varies with drive level.[9,12] In this work it is shown that correcting for non-linearities, an average, representative system response may be obtained. This result is valid for average input signals and modulations.

The MTF of the display is expected to vary with spatial position, being higher at the central area where there is the shortest electron beam travel. Also, the response of the system at one point on the CRT is largely a function of the luminance over the whole screen due veiling glare effects.[19] Thus different backgrounds will give varying results. Since CRTs are not isotropic due to the phosphor and shadow mask structure, and the raster scanning, diagonal MTFs for the central display area should differ from the MTFs measured in this study. Finally, since the composition of the red, green and blue phosphors differ, it is probable that the spatial frequency characteristics are different for each channel. It is nevertheless difficult to evaluate separate channel frequency responses due to secondary emissions result from a single channel input signal.[9,12]

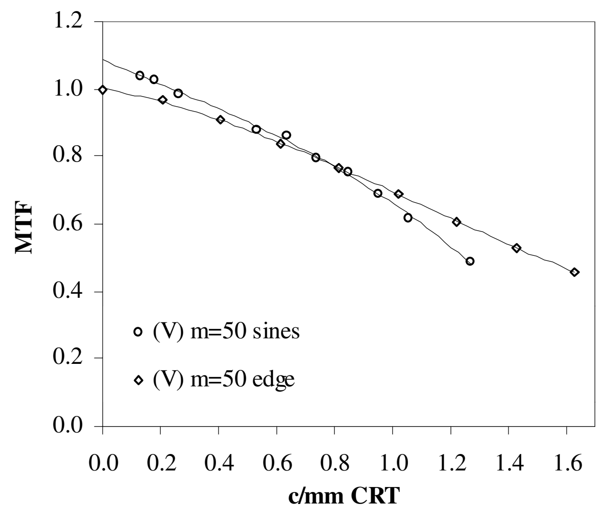

Figure 8. CRT MTFs for the vertical (V) display orientation determined with the sine wave and the ISO 12233 slanted edge methods.

Conclusion

In this study, the MTF of a CRT display system was determined using a digital SLR camera. The sine wave and the ISO 12233 slanted edge methods were employed in the measurements. In the sine wave method, where displayed targets were captured at a very large magnification, Fourier filtering was employed to successfully remove non-linear noise effects. The two measuring techniques gave agreeing results, with the vertical MTF being higher than the horizontal MTF. Despite the fact that the characteristics of the CRT depend on the drive level, different input modulations, ranging from 0.20 to 0.70, resulted to similar spatial frequency responses after the linearization of the output signal. The final MTFs can be used as representative responses of the system once other factors affecting the performance of the display are set to a standard.

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Biography

Sophie Triantaphillidou received a first class honours BSc degree in Photographic and Electronic Imaging Sciences from the University of Westminster in 1995. She is currently a Leverhulme Research Fellow in the Imaging Technology Research Group, having recently completed a PhD project on the digitisation and display of photographic archives. Research interests include issues of image quality of analogue and digital systems.