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FRONT COVER

Garofalo, *Saint Augustine with the Holy Family and Saint Catherine of Alexandria* (NG 81), (detail of PLATE 4, p. 23).

TITLE PAGE

Garofalo, *The Virgin and Child with Saints William of Aquitaine, Clare (?), Anthony of Padua and Francis* (NG 671), (detail of PLATE 3, p. 22).

The MARC II Camera and the Scanning Initiative at the National Gallery

DAVID SAUNDERS, JOHN CUPITT, COLIN WHITE AND SARAH HOLT

Introduction

During the mid-1990s, the National Gallery participated with other museums, universities and commercial companies in the European Community-supported MARC project (Methodology for Art Reproduction in Colour). The two aims of this project were to develop a new large-format digital camera and to incorporate some of the images made with this camera into a publication, using only digital imaging technology, that is, without using traditional 'chemical' photographic processes.¹ The MARC project achieved both of these aims. CCD Videometrie, one of the partners in the project, constructed a camera capable of making images of up to 20000 × 20000 pixels.² Prototype MARC cameras were installed at both the National Gallery and the Alte Pinakothek in Munich. At the latter, 56 paintings were imaged with the camera and resultant data were used to produce all 82 reproductions in a book on Flemish Baroque art, which included details of many of the paintings.³

Once the initial project had been completed in 1995, the Photographic Department at the National Gallery continued to use the MARC camera to make further images of paintings until October 2000, by which time 470 paintings had been imaged. Considerable improvements were made to the image acquisition procedure during these five years. In particular, the tungsten halogen photographic lights were replaced with new, brighter HMI lights that generate less heat.⁴ Because the colour temperature of the light emitted by HMI lamps is in the range 5000-6000K, which more closely matches the target calibration illuminant (D65),⁵ the colour accuracy of the system was much improved.⁶ In addition, the lower heat output of the lamps permits the level of illumination to be increased without increasing the temperature of the painting. This allows the exposure time to be reduced and the aperture to be closed slightly, giving better depth of focus. In general, two HMI lights are placed one either side

of the painting as close to 45° (with respect to the focal axis of the camera) as the surface properties of the painting will permit. This minimises both glare and the accentuation of surface texture.

Even with these advances, making images with the MARC camera was still a slow process. Image acquisition lasted 40 minutes, with a further two hours required for calibration and processing of the images once the acquisition phase was complete and the painting returned to display. Making more than one image a day was difficult, as staff resources were limited. As a result, the rate at which the c.2300 paintings in the collection were being digitised was very slow. This was not really a problem until the decision was made, within the context of the VERMEER project (see below), to incorporate high-resolution MARC digital images of all the National Gallery's paintings in a wider data management system.

The scanning initiative and the VERMEER project

The VERMEER (Virtual Environment for Education, Exploration and Research) project began at the National Gallery in 1999. Its aim is to provide the Gallery with a central database of all the text and images used in publications, ranging from labels to catalogues and CD-ROMs. The VERMEER system is designed to store high-resolution digital images of all the paintings in the National Gallery Collection and to make these, or lower-resolution images derived from them, available for consultation, or incorporation into electronic or paper publications.⁷

To realise this image database, it was clear that the rate of image acquisition would need to increase; at the time the project began, around 100 paintings were being imaged per year with the MARC camera, so that digitising the complete collection would have taken 20 to 25 years to complete. The Gallery made the decision to begin a scanning initiative, with a view to digitising all the paintings on the main floor (including all the most

important paintings in the collection) over a period of eighteen months. This scanning initiative would run alongside the development of VERMEER, so that the images could be integrated into the system. Funds were made available for the additional staff, equipment and studio space that would be needed. A digital photographer, an assistant to process and store the images, and an administrator were employed by the Photographic Department. Extra staff were also taken on by the Art Handling Department to cope with the increased number of paintings that would need to be taken from display, removed from their frames for imaging and returned to the walls at the end of each day. A studio was built in one of the lower floor galleries specifically for digital imaging. The side and rear walls were painted mid-grey, with a black wall behind the easel; this choice of colours ensures that light reflected from the walls does not have a colour cast.

The MARC II camera

A key factor in the decision to undertake the scanning initiative was the availability of an improved version of the MARC camera. This MARC II camera was already in use at the Library of Congress in Washington, having been developed by CCD Videometrie to allow the fast acquisition of photographic documents.⁸ Like the MARC camera, the image is produced by a fairly standard colour CCD, in this case a 1300×1030 pixel device with

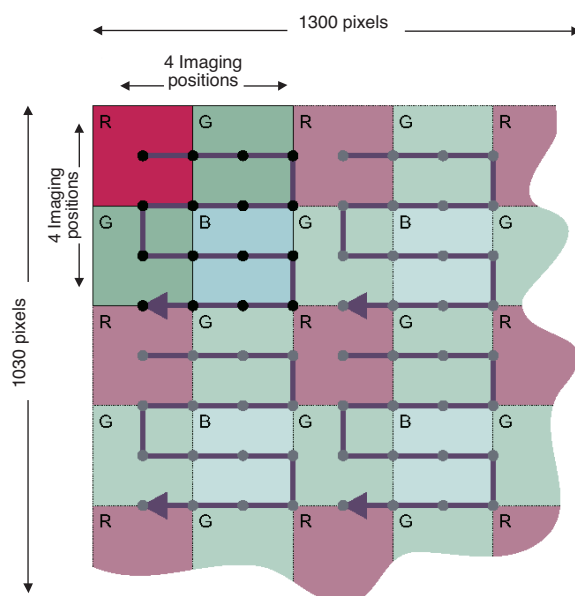


FIG. 1a Schematic showing the micro-positioning pattern for the colour chip in the MARC II camera.

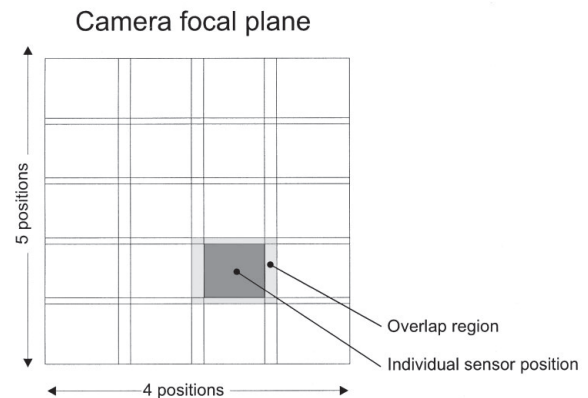


FIG. 1b Schematic showing the effect of macro-positioning the chip in the MARC II camera.

coloured lacquers applied over the photosensitive sites to produce pixels that respond to red, green and blue light. The innovative feature of the MARC and MARC II cameras is that this CCD is moved across the focal plane of the camera to increase the resolution of the image. Two methods are used to increase the resolution: micro-positioning and macro-positioning. Micro-positioning, which in the MARC II camera is achieved by means of piezo-actuators that shift the chip a few microns in the horizontal or vertical direction, serves two functions. First, to increase the resolution of the image, the chip is moved by half the pixel separation in the horizontal and vertical directions to give an image of 2600×2060 pixels. Second, to make a colour image, the set of micro-positioning movements is extended to record information from red, green and blue (RGB) pixels. To do this the sensor moves to sixteen positions during the recording of each frame (see FIG. 1a). This technique, usually termed co-site sampling, produces images that do not have the 'colour fringes' produced by many other imaging devices. Macro-positioning further increases the resolution by moving the whole sensor to $20 (4 \times 5)$ overlapping positions across the focal plane using a positioning stage with two orthogonal motorised axes (FIG. 1b). The combination of micro- and macro-positioning gives a final colour image with a resolution of $c.10000 \times 10000$ pixels.

The MARC II camera has been improved in a number of ways over the previous camera. A higher-quality mechanical positioning system has been used, making the camera suitable for heavy, continuous work. The new sensor has an extremely low dark current, so that it is possible to make long exposures, unlike the MARC I sensor, which could not be used with exposure times greater than one

second. However, as the sensitivity of the new CCD is around 50 times greater than that in the MARC I, long exposures are not necessary. The sensor in MARC II is also temperature-stabilised by a Peltier cooler, increasing the signal-to-noise ratio, while a 14-bit AD converter delivers a high-quality 12-bit linear signal to the controlling computer. The image capture and motor control are separated (on different printed circuit boards) so that when the imaging electronics are in use the motors are automatically turned off, preventing motor noise from affecting the image quality. Finally, an optical fibre link to a dedicated interface board in the controlling computer provides much more reliable data transfer than the previous 50-way copper cable, which had rather fragile connectors.

Camera adaptation and software development

Camera adaptation

The MARC II cameras in use at the Library of Congress had been adapted to operate on a large copy-stand. For the acquisition of images of paintings at the National Gallery, it was necessary to redesign the optics so that the camera could be used to image much larger objects in a photographic studio. As the paintings in the National Gallery Collection range in size from less than 100×100 mm to over 4800×3200 mm, it was decided to fit the two MARC II cameras at the National Gallery with different lenses.

Three criteria determine the focal length of the lens required: the object size, the dimensions of the image plane, and the object-to-image plane distance. The easel in the digital imaging studio can

accommodate paintings up to 2500×2500 mm, while the image plane for the MARC camera measures 31.5×33.0 mm. As the studio is 7200×8000 mm in size, the maximum object-to-camera distance is around 7000 mm, and the most appropriate focal length for the lens is, therefore, 90 mm.⁹ The lens selected was a Rodenstock 90 mm f/5.6 Apo-Sironar digital lens. The manufacturer's specifications indicate that it has low chromatic aberration, low distortion, and a high modulation transfer function.¹⁰ The lens was attached to the camera through a system of threaded rings attached to the front plate of the camera (FIG. 2). By adding or removing these rings, the focal plane-to-lens distance can be changed in 7 mm increments to alter the focus, as the camera-to-object distance is changed depending on the painting size. The digital imaging studio is shown in FIG. 3.

A filter holder is attached to the front of the lens, which carries a Schott BG 40 infra-red-absorbing filter that prevents infra-red radiation falling on the sensor and improves the colour accuracy. As the red pixels in the CCD are sensitive to radiation in the near infra-red, the image quality would be compromised if the infra-red filter were not used. Finally, a lens hood is attached to the front of the filter holder to exclude stray light from the lens (FIG. 2).

For very small paintings, a second MARC II camera is used, which is also fitted with a Rodenstock Apo-Sironar digital lens, but with a shorter focal length. Large paintings that cannot be accommodated in the new studio are being imaged *in situ* at night during the winter months. The camera, HMI lights and computer are moved into the room after the Gallery has closed, when there is no daylight and the artificial lights that normally illuminate the paintings after dark have been switched off.

Software development

As the MARC II camera is supplied with only a device driver and basic image assembly libraries, the user interface and colour management software used by the Digital Photographer to acquire and calibrate images of paintings has been written at the National Gallery. The user interface for the MARC II camera provides a set of controls to move the sensor around the focal plane of the camera, assess and adjust the focus, aperture and exposure, select the area of the focal plane to acquire, and calibrate the camera.

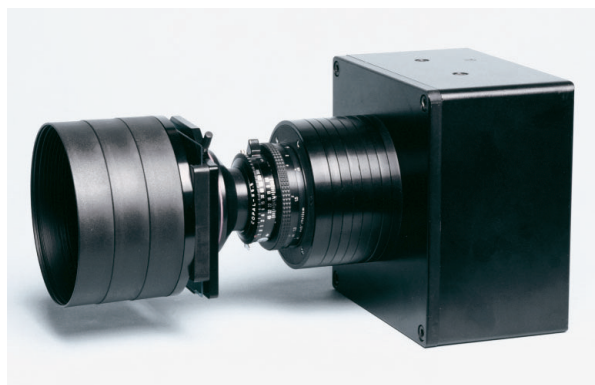


FIG. 2 The MARC II camera; immediately to the left of the lens is the Schott BG40 infra-red absorbing filter. Note the series of 7 mm focusing rings between the lens and the camera body.



FIG. 3 The MARC II camera in use in the digital imaging studio.

The most fundamental calibration is for the underlying hardware; the piezo-actuators and motorised sliders that move the chip are slightly different for each camera, and each needs to be carefully adjusted. A large checkerboard target is placed in the camera's field of view and an iterative process minimises errors in sensor positioning. Once the geometric properties have been determined, a radiometric calibration follows. As each lens has different characteristics, particularly vignetting (that is, the darkening of the image towards the edges of the field of view), a calibration is performed by imaging an evenly illuminated, homogeneous mid-grey target with the lens slightly defocused. This calculates a lightness correction factor for each pixel that also removes differences in sensitivity between sensor elements.

The calibration stages described above only need to be carried out once for a particular camera configuration. In contrast, before each acquisition, the sensor dark current (that is, the small amount of charge that 'leaks' from each pixel even in the absence of light) is measured, and the colour is cali-

brated. Although the dark current is low and the chip is temperature stabilised, most sensors have 'hot spots' where defects in manufacturing make individual pixels particularly sensitive to small changes in temperature. The dark current is measured by covering the lens and grabbing an image at a representative range of exposure settings.

It is necessary to calibrate the colour before every acquisition, since the colour of the illumination can change quite markedly over the lifetime of the lamps. In common with the calibration procedure for the MARC I camera, a Macbeth ColorChecker Chart is placed in the field of view and an image of it made.¹¹ The camera software measures the RGB values from the sensor for each of the 24 patches on the colour chart and calculates a transform from those RGB values to the already known CIE Lab values for the same patch, minimising the errors across the 24 colours.¹² The accuracy of this transform depends on the illuminant and the spectral sensitivity of the red, green and blue filters in the camera chip. As explained on p. 76, since the colour data are calibrated to CIE illuminant D65,

the closer the colour temperature of the lamps to D65, the better the colour accuracy of the resultant image. Using HMI lamps, the MARC II camera gives an average colour error of around 3–4 ΔE units.¹³ The raw images made with the MARC II camera are stored in a file format (VIPS CIE Lab) developed for the MARC I imaging system at the National Gallery, based on the CIE Lab colour space.¹⁴

Image acquisition is very rapid. The host computer has dual Pentium III 550 MHz processors, 1 Gbyte of RAM, and a fast SCSI disc. The camera software can capture a complete 10000 \times 10000 pixel image (including image assembly, dark current and shading correction, deconvolution to remove pixel overlaps, mosaic assembly, colour calibration, conversion to CIE Lab, and writing to disc) in 2 minutes 40 seconds. The camera software can output images in two file formats: a VIPS CIE Lab file (described above) or an 8-bit sRGB file.¹⁵ The latter is useful as a preview image but is not archived.

Workflow

As important as the quality of the images produced has been the administration of the flow of paintings through the studio. In contrast to the original MARC system, where the speed of imaging was the critical factor, the rate at which images are made with the MARC II camera is determined by the practicalities of delivering paintings to the studio and, to a lesser extent, the rate at which the images can be stored as multiple copies on CD-ROM.

The workflow is represented schematically in FIG. 4. Between three and seven paintings per day are requested by the Photographic Administrator, who ensures that the paintings are as far as possible of similar size, to minimise the time spent moving the camera and altering the focus. Paintings from different schools are selected, to avoid depleting the display in a particular room. The art handlers deliver paintings to the studio, remove them from their frames, and return the paintings to display at the end of each day. The Digital Photographer sets up the lighting and camera, calibrates the camera and makes the acquisition as described above. A grey scale and a colour separation guide (Kodak Q-13) are included in each image for reference. The date, painting number, lens aperture, shutter factor and the average colour difference (ΔE) for the Macbeth ColorChecker chart are recorded in a spreadsheet.

After capture, the full-resolution (10000 \times 10000 pixel) image is first cropped to remove the background, but not the grey scale and colour guide, then stored as a VIPS CIE Lab file. The data are also stored as a TIFF CIE Lab file at the same resolution.¹⁶ These two files are passed across the Intranet to the Digital Image Processor who creates two further, derivative, files for archive purposes (see Table 1). The first is a 'medium resolution' file, which has a resolution of 300 pixels per inch (ppi) and is 14 inches on the longest side. These data, which are held in the CIE Lab colour space in a TIFF file format, are intended for use in small-format publications, such as colour plates or covers for books. In the 'low resolution' files, with a resolution of 72 ppi and a maximum dimension of 10 inches, the data are stored in the sRGB colour space in JPEG format.¹⁷ These files are intended for web-based and multimedia applications in which the image will appear on a screen.

Table 1. Digital image files generated by the MARC II imaging programme

Digital file	Colour space	Format	Approx size
Raw high resolution	CIE Lab	VIPS	350 Mbyte
High resolution	CIE Lab	TIFF	270 Mbyte
Medium resolution	CIE Lab	TIFF	30–50 Mbyte
Low resolution	sRGB	JPEG	0.5–1.0 Mbyte

Once all four files have been created, they are allocated a CD-ROM number, and a unique image identification number, taken from the Photographic Department database. Three copies of the set of four files are made on separate CD-ROMs that are stored in the Photographic Archive, the IT store and at an off-site location. A fourth copy of each file is held on the main VERMEER server.¹⁸ The image identification number and image capture details are then recorded in the photographic database.

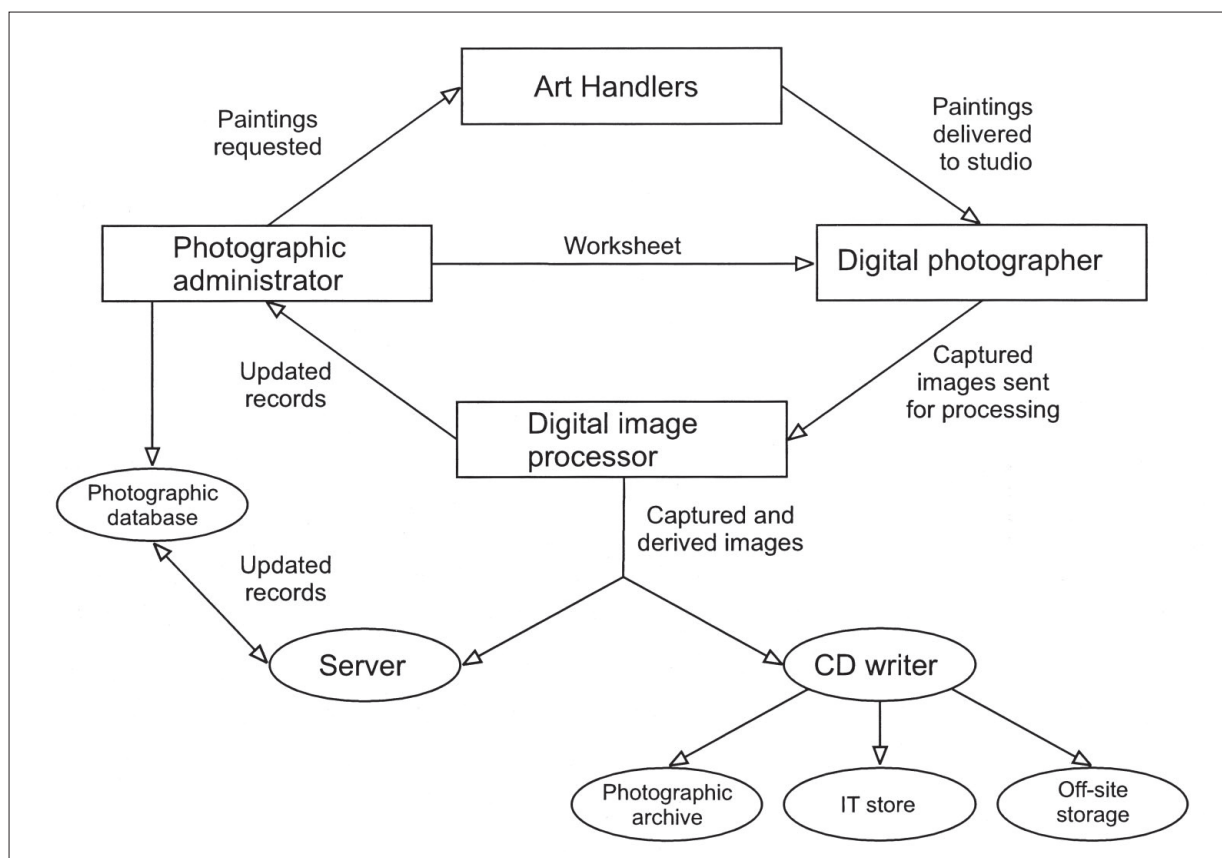


FIG. 4 Work-flow diagram for the National Gallery imaging initiative.

Conclusions

The MARC II camera has been operating successfully at the National Gallery since November 2000. The first target of the scanning initiative, to image 928 paintings by the end of June 2001, was achieved and it is expected that by the end of the second phase, in December 2002, the entire collection (c.2300 paintings) will have been digitised using the MARC system. Stored on the VERMEER system, this set of archive-quality images should meet all the Gallery's requirements, from aiding detailed study of the paintings to providing a source for reproductions. In future, there will be less need to re-photograph paintings, resulting in potentially fewer picture movements and cost savings through reduced use of conventional photographic materials.

The images made with the MARC camera are already being used by the Photographic and Design Departments to produce prints and posters. The images are also of sufficiently high resolution to use in conventional book and catalogue printing. For example, a 10000 × 10000 pixel image reproduced using a 150 ppi screen would cover a sheet of paper approximately 1.7 × 1.7 metres – equivalent to

approximately 48 (6 × 8) sheets of A4 paper. Alternatively, the whole image can be reduced in size by a factor of eight to fit on a single A4 sheet. In practice, the reduced image might be used on one page of a catalogue with one or more details from the high-resolution image on the opposite page. As each reproduction derives from the same 'parent' file, the colour in all the plates should be identical.

Acknowledgements

The authors would like to acknowledge the contributions of Drs Udo and Reimar Lenz, designers of the MARC I and MARC II cameras, Dr Andreas Burmester and Lars Raffelt at the Doerner Institut in Munich, John Downes, who manufactured the camera front plates and lens fixing rings, and at the National Gallery, Steve Dale, the VERMEER project manager. Sir Colin Southgate, one of the Gallery's Trustees, donated one of the MARC II cameras used in the scanning initiative. The European Community ESPRIT III programme supported the original MARC project, while research into printing MARC images has been supported by an external grant from Hewlett Packard, who also donated the VERMEER server to the Gallery.

Notes and references

- 1 The MARC project has been described in a number of publications. A general overview of the project is given in J. Cupitt, K. Martinez and D. Saunders, 'A Methodology for Art Reproduction in Colour: the MARC project', *Computers and the History of Art*, 6, 1996, pp. 1–20.
- 2 R. Lenz, R. Beutelhauser and U. Lenz, 'A microscan/macroscan 3 × 12 bit digital color CCD camera with programmable resolution up to 20,992 × 20,480 picture elements', *Proceedings of the Commission V Symposium: Close range techniques and machine vision, Melbourne, Australia, International Archives of Photogrammetry and Remote Sensing*, 30, 5, 1994, pp. 225–30.
- 3 A. Burmester, L. Raffelt, K. Renger, G. Robinson and S. Wagini, *Flämische Barockmalerei – Meisterwerke der Alten Pinakothek München. Flemish Baroque Painting – Masterpieces of the Alte Pinakothek München*, Munich 1996.
- 4 HMI lamps comprise a quartz envelope containing an atmosphere doped with metal iodides. The light emitted by the lamps is a combination of that from a mercury arc within this envelope and that from the metal iodides. The root of the abbreviation HMI is not entirely clear. The 'H' may refer to the High vapour pressure in the quartz envelope or to the chemical symbol for mercury, Hg. The 'MI' is variously ascribed to a Medium length arc and Iodide or to Metal Iodides. Alternatively, HMI may derive from the German term for this type of lamp Hochdruck Metalliodide (High-pressure metal iodide).
- 5 Reference illuminant D65, with a correlated colour temperature of c.6500 K, is an illuminant recommended for the CIE Lab colour space by the Commission Internationale de l'Eclairage (CIE). See Commission Internationale de l'Eclairage, 'Recommendations on uniform color spaces, color difference equations, psychometric color terms', Supplement No.2 to CIE Publication No. 15 (E-2.3.1), 1971, (TC-1.3) 1978.
- 6 The colour accuracy is measured in ΔE units, where a colour difference of one ΔE unit represents a just visible difference, see R. McDonald and K.J. Smith, 'CIE94 – a new colour difference formula', *Journal of the Society of Dyers and Colourists*, 111, 1995, pp. 376–9. The accuracy of image acquisition is judged by the average colour error for the 24 patches on a Macbeth ColorChecker chart; see C.S. McCamy, H. Marcus and J.G. Davidson, 'A Color-Rendition Chart', *Journal of Applied Photographic Engineering*, 2, No. 3, 1976, pp. 95–9.
- 7 The VERMEER project is designed to facilitate flow of the information used to create publications, and to provide the infrastructure for further Intranet developments. It aims to give the Gallery a centrally managed, accessible and searchable asset repository, which will assist in the production of publications.
- 8 J.R. Stokes, 'Imaging Pictorial Collections at the Library of Congress', *RLG DigiNews*, 3, No. 2, April 15 1999 [ISSN 1093-5371].
- 9 The ideal focal length (f) will be given by the following equation:

$$f = \frac{i \cdot d}{p + i}$$

where p is the painting width or height, d is the distance between the painting and the image plane, and i is the width of the image plane. For p = 2500 mm, d = 7000 mm and i = 33 mm, the focal length, f, will be 91 mm.
- 10 The modulation transfer function (MTF) is a measure of the extent to which a lens can reproduce detail in an image. The MTF can vary with aperture, camera-to-object distance and distance from the focal axis. An ideal lens has a MTF of one across the whole image field, but in practice the MTF is less than one, and decreases with increasing spatial frequency and towards the edge of the field of view.
- 11 See McCamy et al., cited in note 6.
- 12 The MARC system stores colour information for each pixel as three co-ordinates in a standard international system called CIE Lab. The three co-ordinates are termed L*, which represents the lightness of a colour, a* represents a green-red scale (positive values for a* indicating redness, while a negative value symbolises greenness), and b* which represents a yellow-blue scale with positive values of b* signifying yellowness, see Commission Internationale de l'Eclairage, 1978, cited in note 5.
- 13 See note 6.
- 14 The VIPS CIE Lab image format is a 32-bit image that gives greater colour precision than the standard 24-bit image formats most often used to represent colour. See Cupitt et al., cited in note 1.
- 15 sRGB is a standardised version of RGB designed to display acceptably on a wide variety of systems. Most Internet browsers have sRGB as their default colour space. Although it is a well-defined standard, sRGB is a device space, and is thus limited to the range of colours that can be produced by a typical CRT screen. The sRGB standard definition is given at <http://www.color.org/sRGB.html>
- 16 TIFF CIE Lab is a 24-bit image format that retains the colour data in the CIE Lab colour space but has lower precision than the 32-bit VIPS CIE Lab format produced by the MARC camera. For most purposes, however, 24-bit precision is perfectly adequate.
- 17 JPEG is a standard for still-image compression defined by the Joint Photographic Expert Group (JPEG). The commonly available JPEG standards work well only on 24-bit RGB images. Details of the various JPEG standards can be found at: <http://www.jpeg.org/> or through the Independent JPEG Group (whose free JPEG library we use) at: <http://www.ijg.org/>
- 18 All the images are stored on a 1.7 Tbyte Hewlett Packard server. The high-resolution 32-bit VIPS CIE Lab images, the full-resolution and reduced-resolution TIFF images and the JPEG images are accessible across the Gallery Intranet.