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Front cover: Veronese, *The Family of Darius before Alexander*; detail of Plate 11, p. 18

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Elucidating Reflectograms by superimposing Infra-red and Colour Images

DAVID SAUNDERS AND JOHN CUPITT

The great advantage of infra-red reflectography over infra-red photography is the increased penetration of many artists' pigments across the range of wavelengths used by the technique.[1] As a result, paint layers which appear opaque in infra-red photographs, for example those containing azurite, may become transparent in the corresponding reflectogram, revealing the underdrawing beneath.[2]

Unfortunately, this increased pigment transparency in the 1.0 to 2.0μm range can make the relationship between the underdrawing and the final painting less clear. The painted composition can disappear completely from the infra-red image. As a result it may be impossible to determine whether a line of underdrawing revealed by reflectography corresponds with the painted surface or whether the artist has subsequently changed the composition. While the painting is being examined, it is possible to trace features on the surface of the painting with a pointer and to observe the position of this with respect to the underdrawing on the television monitor used with the infra-red camera. Once the painting has been returned to display, however, there is no direct method of relating the assembled infra-red reflectogram mosaic to the painting.

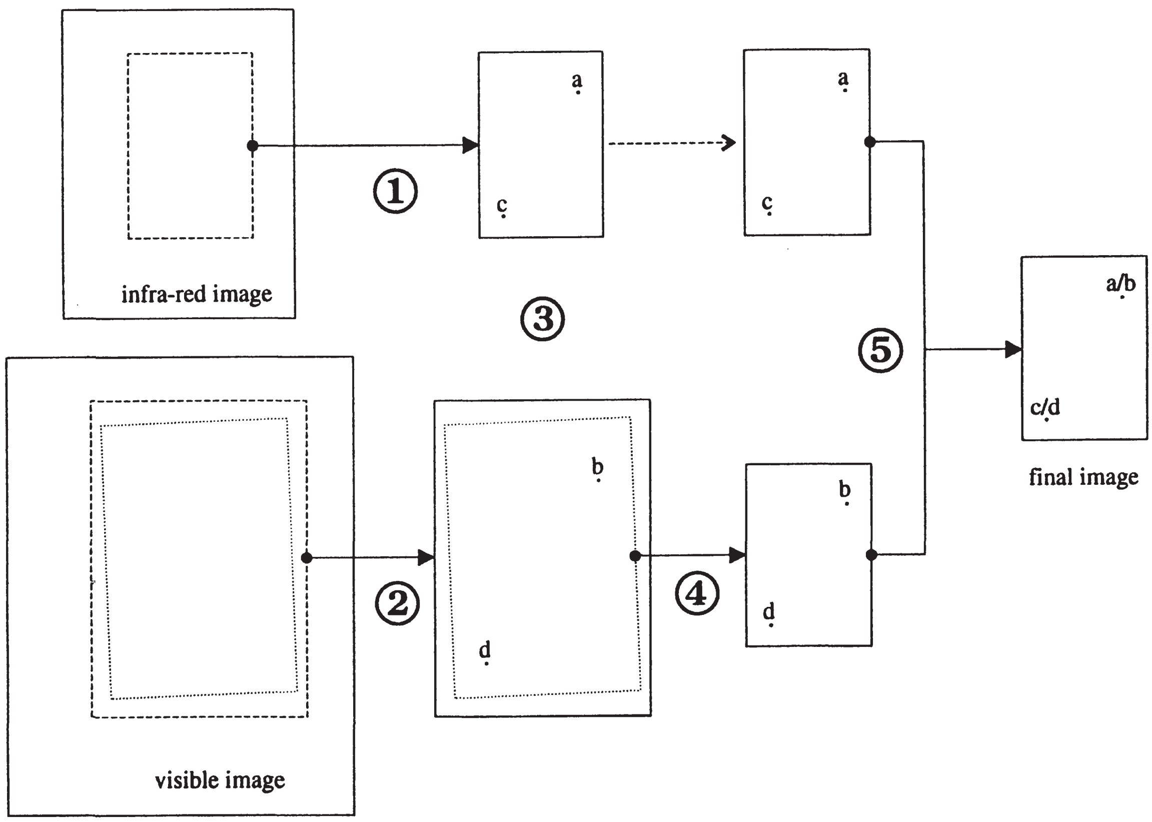

Fig. 1 Schematic representation of the sequence of operations required to produce a 'coloured' infra-red image: 1, a region of interest in the infra-red image is selected and extracted. 2, a corresponding region is selected from the visible image. 3, tie-points are selected. 4, the visible image is resampled using bilinear interpolation. 5, the infra-red and resampled visible images are combined to give a 'coloured' infra-red image.

Since 1992, the National Gallery has been producing infra-red images by digitising the signal from a Hamamatsu N2606 series vidicon camera and assembling composite reflectograms using computer software developed specifically for this purpose.[3] Concurrently, colorimetric images of paintings have been made with the Gallery's VASARI image acquisition and processing system.[4] As the images from these two systems are stored in the same data-file format, it has proved possible to combine images obtained in the visible and infra-red ranges to produce a 'coloured' infra-red image,[5] which provides a clearer picture of the relationship between the underdrawing and the final painting.

The procedure for combining infra-red and colour images

The sequence of operations required to produce a 'coloured' infra-red image is controlled by a single image processing software program[6] and is shown schematically in Fig. 1. The two starting images for the process are a high-resolution colour image of the painting (typically above 10 pixels mm^{-1}) and the assembled infra-red reflectogram mosaic. The latter image generally has a somewhat lower resolution and has been sharpened, using a spatial filter.[7] The first operation is to select a region of interest on the infra-red image of the whole painting and to extract this sub-image, step 1 in Fig. 1. The time taken to process the images and the inaccuracy in superimposition are greatly reduced if a limited area is chosen. The region extracted from the visible image, step 2, corresponds to the region extracted from the infra-red image, but covers a slightly larger area of the painting.

The next stage is to select tie-points in the infra-red and visible images, step 3 in Fig. 1. The tie-points indicate corresponding positions in the two images and must be selected with great care, as the selection cannot be improved by correlation.[8] Because the object of this image combination is to differentiate between features in the underdrawing and in the paint layers, tie-points are selected that are independent of the subject matter of the painting. Typical features for the tie-points include distinctive craquelure, paint losses and retouchings.

Once the tie-points have been selected, the computer uses the coordinates to determine a similarity transformation for the visible image that will bring these points into coincidence.

The similarity transformation is first-order, comprising rotation, scaling and translation only. The visible images, produced by a solid-state camera, generally have good geometric qualities. In contrast, the infra-red images, which originate from the lead sulphide detector in the vidicon, have poor geometric properties. To bring large areas of the two images into exact coincidence would require the selection of an impossibly large number of tie-points and would be very intensive computationally. The similarity transformation used gives errors of the order of 1 pixel in 300 (0.3%); for a typical 'coloured' infra-red image of 1500 by 1500 pixels, alignment errors of up to about 5 pixels are expected. Since alignment is not pixel-perfect, the visible image is only resampled using bilinear interpolation, step 4. The best results are achieved if the tie-points are as far apart as possible, as shown in Fig. 1, and, because of the alignment error, are as close as possible to features of particular interest in the infra-red reflectogram.

Finally, the two images (infra-red and resampled visible) are combined to give a 'coloured' infra-red image, step 5 in Fig. 1. The proportion of visible to infra-red image can be controlled to highlight the information required. A ratio of between 1:1 and 1:2 (visible to infra-red) has been found to provide clear images.

The technique in use

Two examples of the use of this technique are given in the accompanying illustrations. Fig. 2 shows a detail from the computer-assembled infra-red reflectogram of *The Lamentation over the Dead Christ* from the workshop of Rogier van der Weyden (NG 6265). Plate 1 shows the corresponding area of the visible image after resampling; the tie-points selected were in areas of craquelure on Christ's chest and legs. In Plate 2 the resampled visible and infra-red images have been combined in a ratio of 1:1. Comparing Plate 2 to Fig. 2 it is possible to see some of the changes between the underdrawing and the final painted image. The changes in position of Mary's hand and Christ's loincloth

Plate 1 Detail from the visible image of *The Lamentation over the Dead Christ* from the workshop of Rogier van der Weyden, showing the area corresponding to Fig. 2 after resampling.

Fig. 2 Detail from the computer-assembled infra-red reflectogram of *The Lamentation over the Dead Christ* from the workshop of Rogier van der Weyden.

Plate 2 'Coloured' infra-red image created by combining Fig. 2 and Plate 1.

Fig. 3 Detail from the computer-assembled infra-red reflectogram of the *Portrait of a Young Man* by the Master of the View of Sainte Gudule.

Plate 3 'Coloured' infra-red image for the *Portrait of a Young Man* by the Master of the View of Sainte Gudule.

are evident in the infra-red image, but are seen more clearly in the 'coloured' version. The more subtle changes to the modelling of Mary's robe are not apparent in the reflectogram as both the pigments used – red lake and lead white – are penetrated by the infra-red. In the 'coloured' infra-red image, the disparity between the original lines, drawn to mark the position of the folds, and the areas of light and shadow in the final painting can clearly be seen.

A second example is given in Fig. 3 and Plate 3, which show, respectively, a detail from the infra-red reflectogram of the *Portrait of a Young Man* by the Master of the View of Sainte Gudule (NG 2612) and a 'coloured' infra-red image. To achieve good coincidence between the infra-red and visible images, the reflectogram in Fig. 3 was first divided into two smaller images. Corresponding regions from the visible image were resampled and then combined with the infra-red images in the manner described above (ratio 1:1). Finally, the two 'coloured' images were joined again to give the image in Plate 3; the join is just noticeable on the right edge at the level of the shoulder.

Most of the changes between the drawing and the painting are easy to see in the reflectogram: for example, the alteration to the line of the man's shoulder and the various small figures in front of the church. Less obvious without the help of the 'coloured' image are the changes in the background to the right of the man's hat. Here the well was drawn larger, a wall extended behind the trees on the right, and various small buildings were drawn to be replaced by trees or bushes in the painted version. There are alterations in the church; for instance, on the extreme left a window has been painted which was not drawn. The reflectogram also shows changes at the drawing stages. There are for example two lines for the nose and it is not immediately apparent which was followed at the painting stage. Reference to the 'coloured' image clearly shows that the nose was enlarged.

Further examples of the use of 'coloured' infra-red images may be found in the article describing the results of the infra-red examination of *The Portrait of Giovanni (?) Arnolfini and his Wife Giovanna Cenami (?)* by Jan van Eyck (NG 186); see pp. 47–60 of this *Bulletin*.

Conclusions

The procedure for combining images made in the infra-red and visible ranges is proving to be a useful additional tool in the interpretation of reflectograms. While the colour images used in these examples were made using the specialised VASARI image acquisition system, there is no reason why the visible images should not be obtained from another source, for example by digitising colour transparencies using a desk-top scanner. Using such a scanner it is also possible to digitise information from other types of image, such as X-radiographs; we are extending this work to use the same resampling techniques to bring X-radiographs and visible images into coincidence.

Although these resampling algorithms are not very refined, the poor geometric properties of the infra-red reflectogram mosaics do not warrant the development of a more sophisticated procedure. A marked improvement in the accuracy of coincidence would most easily be achieved by replacing the vidicon by an imaging device with inherently better geometric characteristics such as an infra-red sensitive solid-state camera, based for example on a platinum silicide (PtSi) detector.

Acknowledgements

All the infra-red reflectograms used in this study were acquired and assembled by Rachel Billinge. The computer software for image matching and resampling was initially developed by Jean-Philippe Laurent, from the Ecole Nationale Supérieure des Télécommunications, Paris. The authors would also like to thank Lorne Campbell for his helpful comments and encouragement.

Notes and references

1. Van Asperen de Boer identified the 1.0 to 3.0µm range as the region of the spectrum most likely to give good penetration of paint layers and good visibility of the underdrawing materials; see J. R. J. van Asperen de Boer, 'Infrared reflectography', thesis, University of Amsterdam, 1970.
2. The search for imaging devices that give increased pigment transparency, and increased visibility of underdrawing, in the near infra-red region has been extended to include a number of solid-state cameras, including those based on germanium and platinum silicide; see J.K. Delaney, C. Metzger, E. Walmsley and C. Fletcher, 'Examination of the visibility of underdrawing lines as a function of wavelength', *Preprints of the International Council of Museums Committee for Conservation,* 10th triennial meeting, Washington DC 1993, pp. 15–19.
3. R. Billinge, J. Cupitt, N. Dessipris and D. Saunders, 'A note on an improved procedure for the rapid assembly of infrared reflectogram mosaics', *Studies in Conservation*, 38, 1993, pp. 92–8.
4. D. Saunders and J. Cupitt, 'Image processing at the National Gallery: The VASARI project', *National Gallery Technical Bulletin,* 14 , 1993, pp. 72–85.
5. In this context the term 'coloured' is used to refer to images produced by superimposing colour information (from an image captured using visible light) on to a digitised infra-red reflectogram image of the same region of a painting. These 'coloured' images should not be confused with false-colour infra-red images, which are created by assigning the red, green and blue components of a colour image to reflection in the infra-red, red and green regions of the spectrum respectively. The photographic version of the latter technique is described in M. Matteini, A. Moles and P. Tiano, 'Infrared colour film as an auxiliary tool for the investigation of paintings', *Preprints of the International Council of Museums Committee for Conservation,* 5th triennial meeting, Zagreb 1978, 78/1/3/1–9; false-colour images have also been produced by image capture with a CCD camera using appropriate filters, see A. Aldrovardi, D. Bertani, M. Cetica, M. Matteini, A. Moles, P. Poggi, and P. Tiano, 'Multispectral image processing of paintings', *Studies in Conservation,* 33, 1988, pp. 154–9.
6. The processing of all the images is controlled by the computer programme IP, using the VIPS (VASARI Image Processing System) library of image processing functions; see D. Saunders and J. Cupitt, cited in note 4, p. 84 n.3, p. 85, n.11. This software has been developed as part of European Community-funded ESPRIT projects VASARI (No. 2649) and MARC (No. 6937). A more detailed description of the software is given in J. Cupitt and K. Martinez, 'Image Processing for Museums', in *Interacting with Virtual Environments*, ed. L. MacDonald and J. Vince, London 1994, pp. 133–47.
7. See note 3.
8. When matching two visible or two infra-red images, for example during mosaic assembly, it is possible to use the maximum of a correlation surface to improve the choice of tie-points and therefore to provide a better match between the two images. When, however, this procedure is used on a visible and an infra-red image, the correlation between the two images is so low that such a refinement is not possible.