

High-resolution infrared imaging

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ABSTRACT

The hands and mind of an artist are intimately involved in the creative process of image formation, intrinsically making paintings significantly more complex than photographs to analyze. In spite of this difficulty, several years ago the artist David Hockney and I identified optical evidence within a number of paintings that demonstrated artists began using optical projections as early as c1425—nearly 175 years before Galileo—as aids for producing portions of their images. In the course of our work, Hockney and I developed insights that I have been applying to a new approach to computerized image analysis. Recently I developed and characterized a portable high resolution infrared for capturing additional information from paintings. Because many pigments are semi-transparent in the IR, in a number of cases IR photographs ("reflectograms") have revealed marks made by the artists that had been hidden under paint ever since they were made. I have used this IR camera to capture photographs ("reflectograms") of hundreds of paintings in over a dozen museums on three continents and, in some cases, these reflectograms have provided new insights into decisions the artists made in creating the final images that we see in the visible.

Keywords: infrared reflectography, Renaissance paintings, image analysis, David Hockney

1. INTRODUCTION

Ultraviolet light (UV; $\lambda < 400$ nm) excites fluorescence in many materials in the visible (400 nm $< \lambda < 750$ nm) as well as the infrared (IR; $\lambda > 750$ nm), and IR light penetrates further through many pigments than does visible light. Because of these optical properties, imaging works of art in the IR that are illuminated by UV, visible, and IR can provide considerable additional information over that available in the visible alone. For example, the presence of underdrawings made with materials having different optical properties than those of the overlaying paint often can be detected by photographing the artwork in the IR. IR reflectography¹ as a technique for the examination of works of art was introduced in the 1960s by R.J.R. van Asperen de Boer,² and has provided many valuable insights into the working practices of a number of artists.^{3,4}

Commercial imaging systems designed specifically for IR reflectivity are available that provide sub-mm resolution over the wavelength range 900–1700 nm using an InGaAs sensor, with an image acquisition time of 2 minutes at an illumination level of 250 lux.⁵ Unfortunately, such systems cost over \$50,000 and are not very portable, and the cost and specialized nature of the equipment has significantly restricted its use. As a result, only a small percentage of paintings in museum collections have been examined with this technique to date.⁶ However, as described in detail elsewhere,⁷ recently I developed an inexpensive, high resolution IR camera for the purpose of IR reflectography, allowing *in situ* acquisition of images in a way that is minimally disruptive to the operation of a museum. Although this modified consumer camera is limited to an upper wavelength of 1100 nm, the resolution is as high as 0.05 mm with an image acquisition time only a fraction of a second at 250 lux. The capabilities of this camera are illustrated in this manuscript with examples from several museums.

1.1 Si-based sensors for Infrared (IR)

Recently, cameras based on Si, InGaAs, HgCdTe and InSb detectors for capturing IR reflectograms were compared based on the relative transparency of various pigments in the wavelength range 400–2500 nm.⁸ The authors concluded that, although some pigments are better studied with detectors that are sensitive in the range 1300–2200 nm, in most cases Si-based detectors provide good results. The present manuscript describes results obtained with a system based on

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the Si detector in a modified commercial Canon digital camera that can be easily operated by non-specialists and costs less than \$2000.⁹ This camera has a 2336×3504 silicon-based complementary metal oxide semiconductor (CMOS) array at the focal plane to convert the energy from incoming photons into electronic charge that is then processed to form the file for each image. Operation relies on the absorption of light by the silicon, which occurs for photon wavelengths up to the bandgap of 1.12 eV (1110 nm), beyond which the Si becomes transparent. It is this sensitivity to IR that makes the CMOS array useful for IR reflectometry. The sensitivity of the sensor in this modified camera is illustrated in Figure 1.

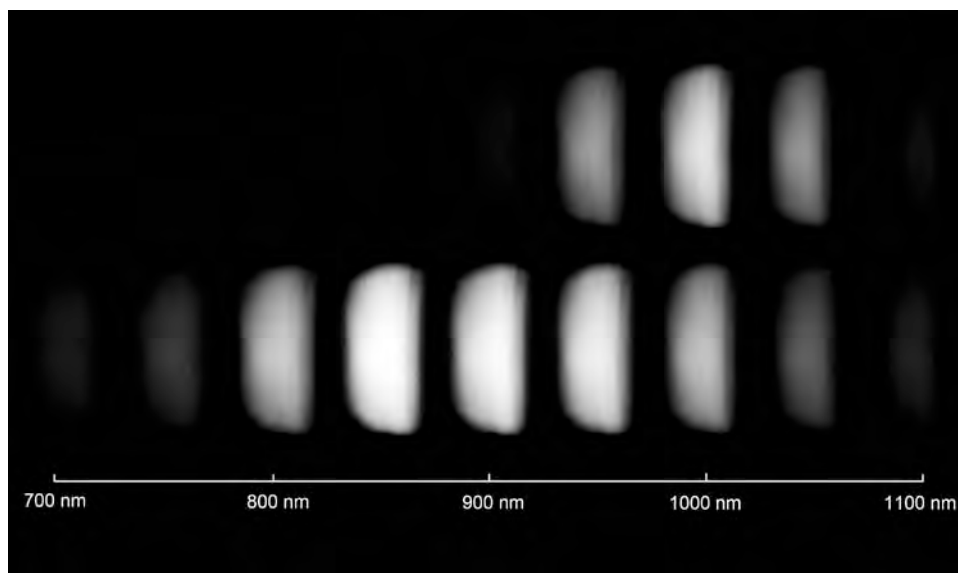


Figure 1. Relative sensitivity of modified Canon camera, measured by imaging the output slit of a calibrated spectrophotometer using equal exposure times at each wavelength. **Lower)** the modified camera. **Upper)** with an additional "1000 nm" high-pass cutoff filter over the lens, measured using exposure times 8× longer than without this filter.

As can be seen from the lower portion of Figure 1, the sensor of the modified camera has peak sensitivity around 900 nm. The upper portion of this figures shows that a "1000 nm" high-pass filter added to the front of the lens moves the peak sensitivity approximately 100 nm further into the IR. However, doing so loses the autofocus function of the camera, and reduces the light intensity at the sensor by approximately 8×. Despite these disadvantages, there are times when this additional capability can be valuable.

A recent paper also addressed use of a commercial digital camera for acquiring IR reflectograms, but the implementation described in that paper requires bandpass filters in front of the lens.¹⁰ As noted in the previous paragraph, such filters eliminate all visible light from the viewfinder and from the autofocus and light metering systems, requiring that alignment and focusing be based on measured distances to the painting, and exposures determined entirely by trial and error.¹¹ The IR camera described below eliminates these limitations, resulting in a camera system that can be easily operated by non-specialists. However, several technical issues affect the ability to capture IR images in the range 830–1100 nm when modifying a camera that was designed for operation in the visible. These issues are addressed in detail elsewhere.⁷

1.2 Optics for the Infrared (IR)

Suitable optics for focusing images in the IR is not a problem, since the glass used in consumer camera lenses transmits light from approximately 350 nm in the ultra-violet, through the visible of 400–750 nm, and into the IR. The specific camera system I have developed for IR reflectography is based on a Canon EOS 30D body with 22.5 x 15 mm, 8 MPixel sensor. The images in this manuscript were made with either of two autofocus Canon EF lenses; 35 mm f/2 or 20 mm f/2.8.^{12,13} However, since IR comes to focus at a different distance than does visible light, this sensitivity to wavelengths longer than 750 nm is a problem for a camera intended only for the visible.¹⁴ For this reason the manufacturer places a low pass filter directly over the CMOS array to eliminate all IR from reaching the detector. The modification described

elsewhere⁷ removes this IR-blocking filter, replaces it with a visible-blocking filter, and offsets the electronics to compensate for the slightly different focal length of the lens in the IR.

1.3 Comparison with Visible Light Images

It is very helpful to take images of the paintings at the same time with an unmodified camera as well. Even if the image files from the two cameras are not of the same size, and if they were taken from somewhat different positions, it is easy to accurately and automatically resize and align them with a program such as PhotoShop®.¹⁵ For studying the images I find it useful to create three layers in PhotoShop®: color, as captured by the unmodified camera; monochrome, converted from the color image; and IR.

2. EXAMPLES OF INFORMATION FROM IR IMAGES OF PAINTINGS

The information an IR camera provides about works of art has a variety of uses. The examples in this manuscript are limited to two-dimensional art, but there also are many uses for three-dimensional cultural objects, such as pottery, sculpture, and costumes.⁷

2.1 Revealing underdrawings

Various additional lines and features in Figure 2 are revealed in the IR. For example, by comparing the visible and the IR images, it can be seen that the ledge outside the window originally had a rounder shape, and that it and the hinge attaching it were painted before the box-like apparatus on the ledge was added (the outline of the ledge and hinge can be seen through the box-like-apparatus, indicating they were painted first). This reflectogram also illustrates a difficulty sometimes encountered with *in situ* operation. The broad, bright features just below the window, and crossing one post of the chair, are due to direct reflections of a light source from the protective glass covering this particular painting. However, since glass is transparent to IR, this example shows that even where a reflection cannot be eliminated by repositioning the camera, quite useful results still can be obtained.



Figure 2. "Merode Altarpiece," Robert Campin, c1425 (20×17.6 cm detail). **Left**) visible image, with details marked in red that are revealed by the IR reflectogram, but which are not seen in the visible image. **Right**) infrared. Metropolitan Museum of Art.

2.2 A painting that has been extensively restored

Figure 3 illustrates the degree to which paintings can appear different in the visible and the IR due to the optical properties of the pigments used on the painting. As is revealed by the IR reflectogram, this painting has been extensively restored using pigments that are quite reflective in the IR. Both of these images were captured without a tripod, under standard museum lighting conditions. Despite this, as can be seen, the resolution of the images is high.



Figure 3. "The blessed Ranieri frees the poor from a Florentine jail," Stefano di Giovanni, known as Sassetta, 1437/1444 (43×63 cm). **Top**) visible light. **Bottom**) infrared. Louvre Museum.

2.2 Selective use of a particular pigment

Figure 4 is a detail of an 1898 painting by Camille Pissarro, one of the major figures in the French Impressionist movement. Comparing the visible light image with the IR reflectogram in Figure 4 immediately reveals the use of two different pigments of nearly identical color on the store fronts. The fact one of these pigments is significantly less transparent in the IR than the other allows us to see that one of them was used for only a few features. This fact is not apparent from the visible image alone.

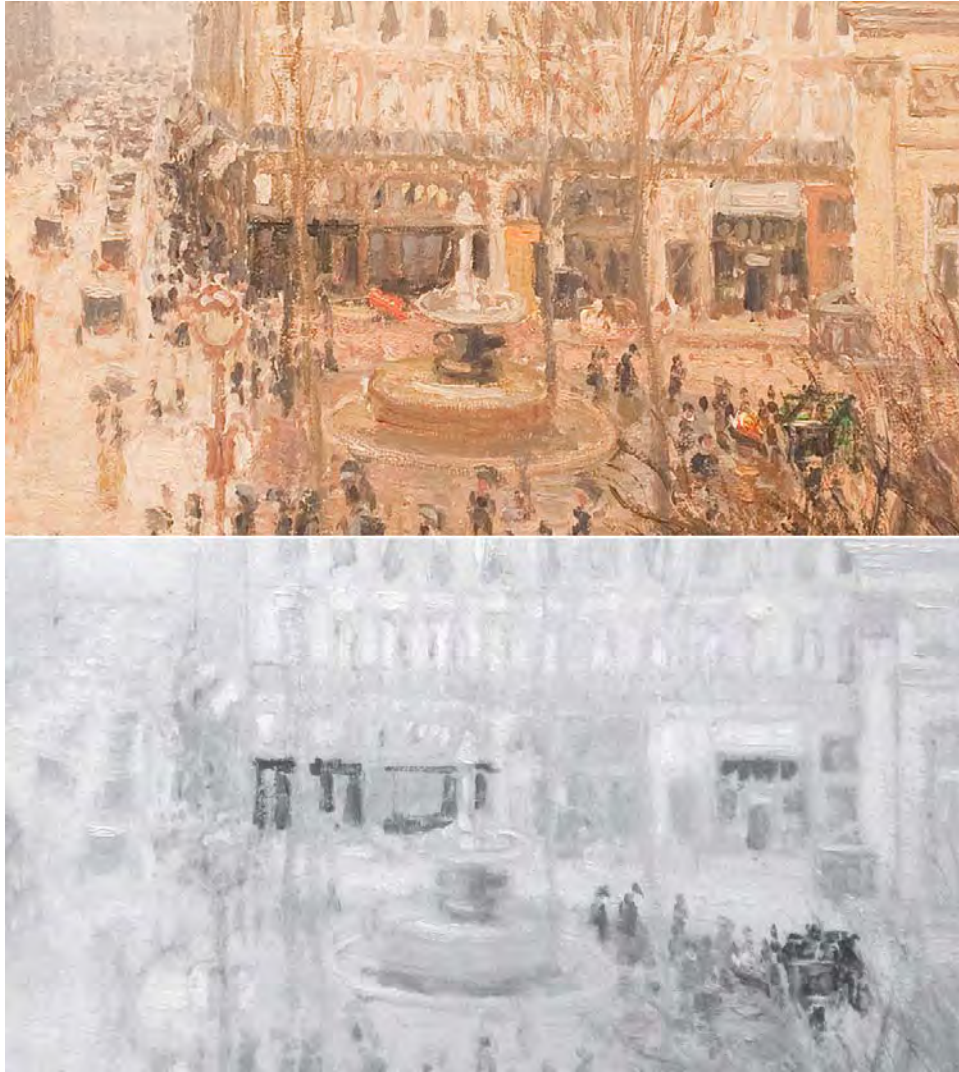


Figure 4. "Avenue de l'Opera," Camille Pissarro, 1898 (35×19 cm detail). **Top**) visible light. **Bottom**) infrared. Minneapolis Institute of Arts.

2.1 Evidence a lens was used to project certain features

Several years ago the artist David Hockney observed features in a number of paintings that lead him to conclude some artists began using optical projections as aids as early as c1425.¹⁶ Together Hockney and I subsequently found a variety of optical evidence in a number of paintings that demonstrated artists as important as Robert Campin, Jan van Eyck, Hans Holbein the Younger, Caravaggio, and others used projected images from lenses or concave mirrors as direct aids for producing some features of some of their paintings.¹⁷ As a result, such paintings are complex composites, consisting of elements directly traced from projected images, elements based on optical projections but with modifications made by

the artist to suit his artistic intent, and elements created solely from the artist's imagination. One painting, "Family Portrait" by Lorenzo Lotto (1523/1524),¹⁸ was particularly valuable in providing quantitative evidence for our thesis. It contains an octagonal pattern in the table covering that we showed to an accuracy of better than 1% consists of three segments, at three magnifications, resulting from the refocusing necessitated by the depth-of-field of a lens. This allowed us to calculate the focal length and diameter of the lens Lorenzo Lotto would have had to use in order that these features should correspond so accurately to the laws of geometrical optics.¹⁷

Figure 5 is the full image of this painting in the visible that I captured *in situ* using an unmodified Canon 5D camera with a Canon 35 mm f/2 lens. Examination of this image reveals some of the obstacles facing *in situ* image capture in a museum environment. The painting was illuminated by a combination of indirect sunlight from windows to the left, and overhead tungsten lights, each having its own color temperature. The shadows visible along the left and top borders were cast by the ornate frame in which the painting is mounted. The roughly equal darkness of these shadows indicates that the level of illumination from both types of sources was approximately equal. Closer inspection shows that the illumination across the surface of the painting is not uniform. This can be most easily seen in the region of the man's chest, which is too bright due to a partial specular reflection of one of the light sources that could not be eliminated by repositioning the camera within the constraints of the room. However, in spite of these obstacles, I was easily able to obtain IR reflectograms that have revealed important new information about this painting, and added further evidence that Lotto used a lens to aid him in producing certain features on the table covering.

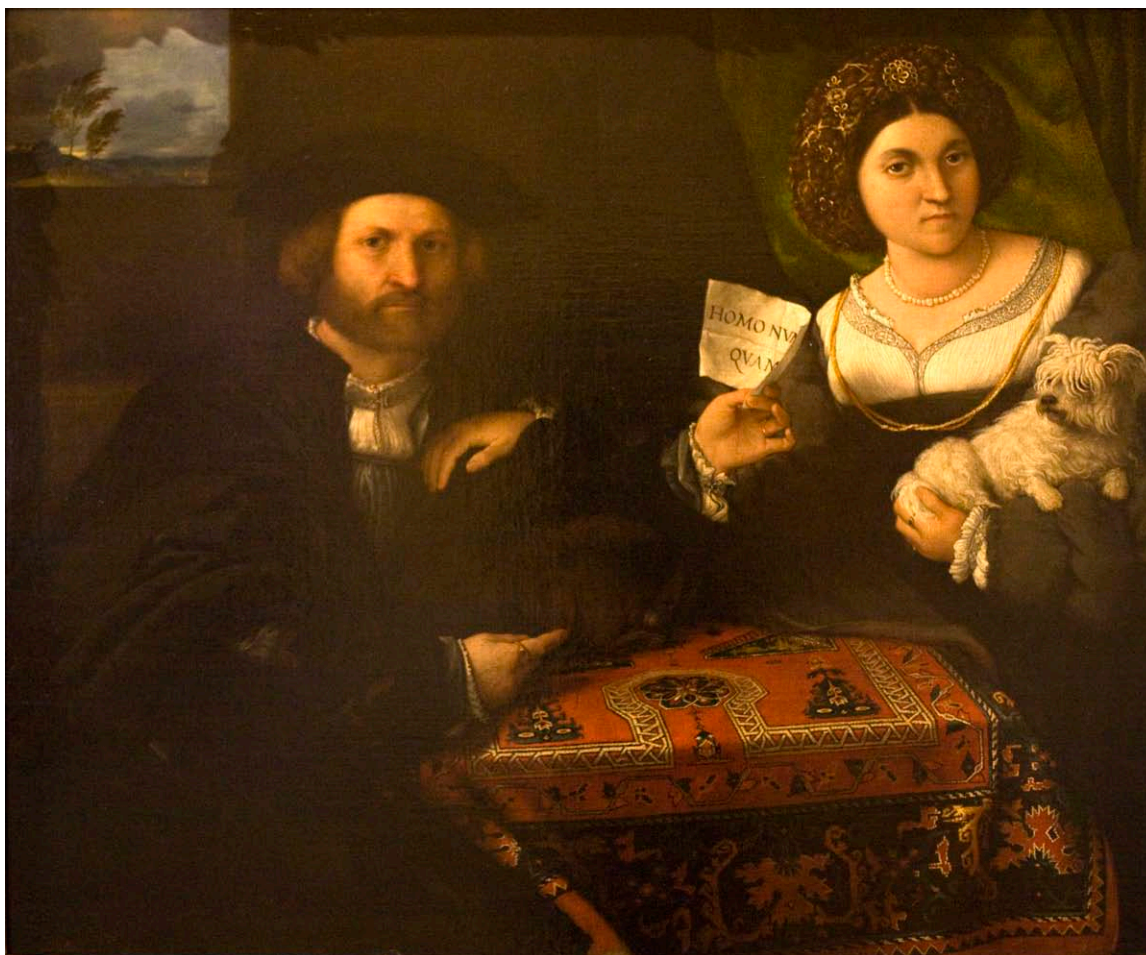


Figure 5. "Family Portrait," Lorenzo Lotto, 1523/24 (96×116 cm oil on canvas). Hermitage State Museum.

Figure 6 is an IR reflectogram of the full 96×116 cm painting, captured under the less than ideal lighting conditions described in the previous paragraph. The exposure was 1/4-sec. at f/4 with an ISO of 100. As discussed elsewhere,⁷ these represent optimum conditions for noise and resolution from this imaging system, and have resulted in a measured resolution on this image of better than 0.5 mm. Also, the same 35 mm f/2 lens as used for Figure 5 was used here as well. Although many features are revealed by this IR reflectogram, one immediate observation is that Lotto used a different pigment for the woman's dress than he used for the man's jacket, providing us with previously unknown information about the artist's working technique.



Figure 6. IR reflectogram of "Family Portrait," Lorenzo Lotto, 1523/24 (96×116 cm oil on canvas) captured *in situ* using tripod-mounted modified Canon 30D with 35 mm f/2 lens. Hermitage State Museum.

Figure 7 shows the octagonal pattern of the table covering in greater detail, enlarged from an image taken from approximately half the distance as used for Figure 6 (so the resolution at the plane of the painting is ~0.25 mm). As can be seen by comparison with Figure 5, the red and yellow pigments Lotto used are largely transparent in the IR, providing us with a clear view of the black lines he used to create this feature on the painting.

Three distinct types of markings can be clearly seen for the lines making up the triangular pattern: well defined lines in the 3 cm region nearest the front of the image, consistent with tracing a projected image. These "traced" lines abruptly change to tentative lines in the middle region, where our previous analysis showed the magnification was reduced by $12.6 \pm 1.5\%$ due to refocusing (compare with Figure 1 of Ref. 17). Because of this, Lotto would have had significant difficulty creating a plausible match for this geometrical pattern after refocusing. His abrupt change to tentative lines reflects this difficulty. The quality of the lines again abruptly changes to only short dashes in the region farthest into the

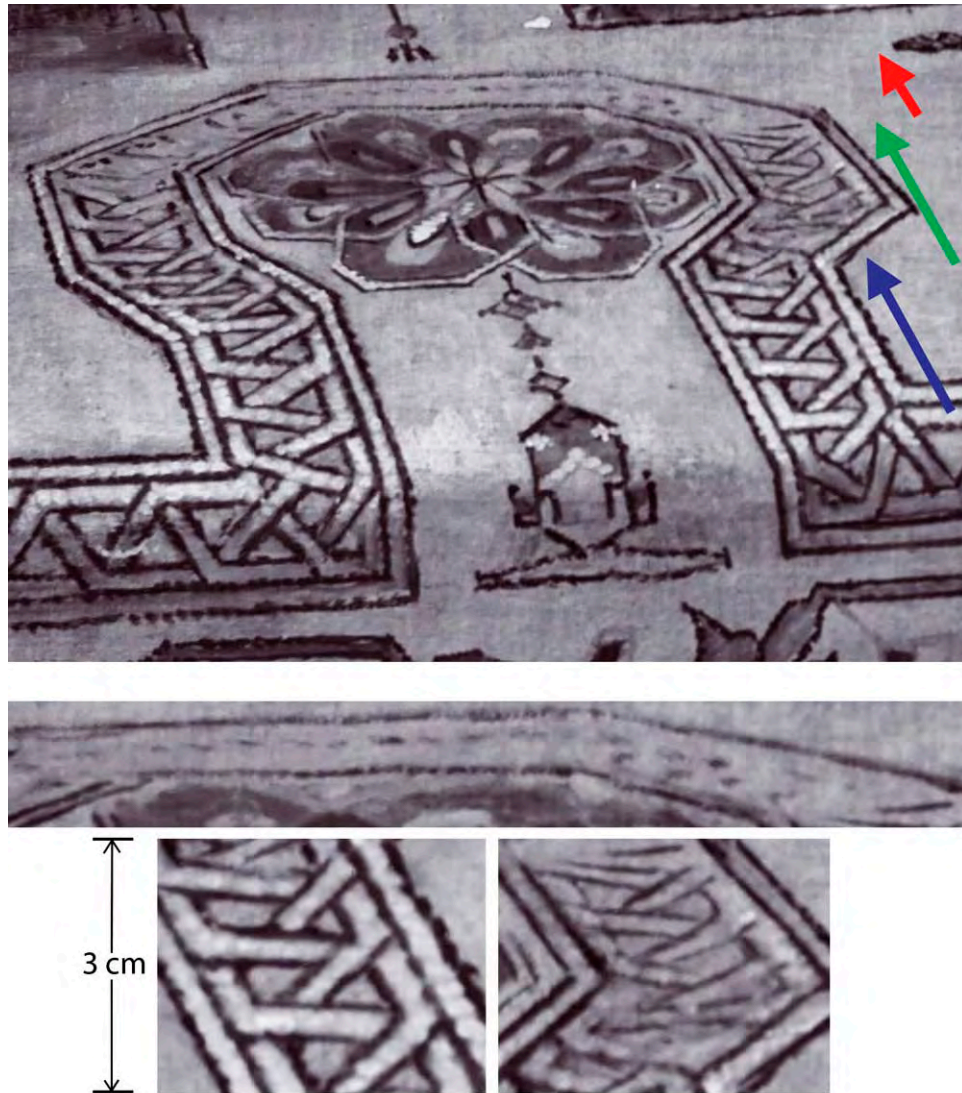


Figure 7. **Top)** IR reflectogram of the octagonal pattern from Figure 6. The arrows superimposed to the right indicate the three regions our previous analysis of this painting found,¹⁷ from which we were able to demonstrate this feature is based on an optical projection. Our calculations showed that each time the depth-of-field forced the artist to refocus, the magnification was reduced by ~13%. **Bottom)** The three insets are 175% enlargements of the triangular patterns from the three regions at the right of the octagonal feature. Each inset is of a region 3 cm or less high. Consistent with our previous analysis, these IR reflectograms show Lotto abruptly changed between making lines that appear traced (**lower left**), to lines that are hesitant where he had to attempt to construct a plausible match to a geometrical pattern after the magnification had changed by 12.6% (**lower right**), to just a few dashed lines after the magnification had changed a second time by an additional 13.5% (**upper inset**). Compare with Fig. 1 of Reference 17.

scene, where our previous analysis shows the magnification was reduced by an additional $13.5 \pm 1.6\%$ due to having to refocus a second time after again reaching the limit of the depth-of-field. These results from IR reflectography provide important additional insights into the actual working practices of an artist, revealing quite specific details about how he made use of projected images over 150 years prior to the time of Galileo.

Our previous analysis of this painting¹⁷ found a change in the vanishing point that takes place part way back in the pattern in the border of the carpet to the right, quantitatively consistent with the change that is caused by the shift in position of a lens as it is refocused. Figure 8 shows the IR reflectogram of this portion of the painting. Overlaid to the

left are seven units of a perfectly repeating structure that replicates the geometrical pattern of the border (note: a triangular structure could be used instead, but the structure used in Figure 8 makes it somewhat easier to see the underlying pattern on the painting for comparison). As can be seen, when corrected for optical perspective, this repeating structure is an excellent fit to the pattern near the front of the carpet, with a maximum deviation of 2 mm, consistent with the degree of perfection found in the hand-made carpets of this type.¹⁹ Although an eighth unit of the structure does not fit at all (not shown), a small change in optical perspective makes the same repeating structure fit at the rear, again to within better than 2 mm. This change in perspective occurs at the same depth into the painting where our previous analysis found a shift in vanishing point, as happens when a lens is repositioned to focus further into a scene.¹⁷ In addition, not only does the perspective change where this present analysis as well as our previous one indicates Lotto had to refocus, the pattern on the painting is missing a half-segment of the repeating pattern at this location. This is consistent with Lotto attempting to create a plausible match between two segments of a repeating structure after refocusing had caused the magnification to change. Again, all of these detailed findings from IR reflectography are consistent with our earlier work that showed this portion of the painting is based on the optical projection of an actual hand-made carpet. I note that we have used 14th century optical technology (i.e. one lens of a pair of reading spectacles, as well as a metal concave mirror we fabricated following descriptions in texts of the time) to accurately reproduce all of the effects we have found in this carpet, and in all of the other paintings we have shown to contain elements based on optical projections,^{16,17} including projecting such patterns directly on a screen of the same shade of red used in this painting. Even on such a colored screen, the projected images are quite distinct and easy to trace.

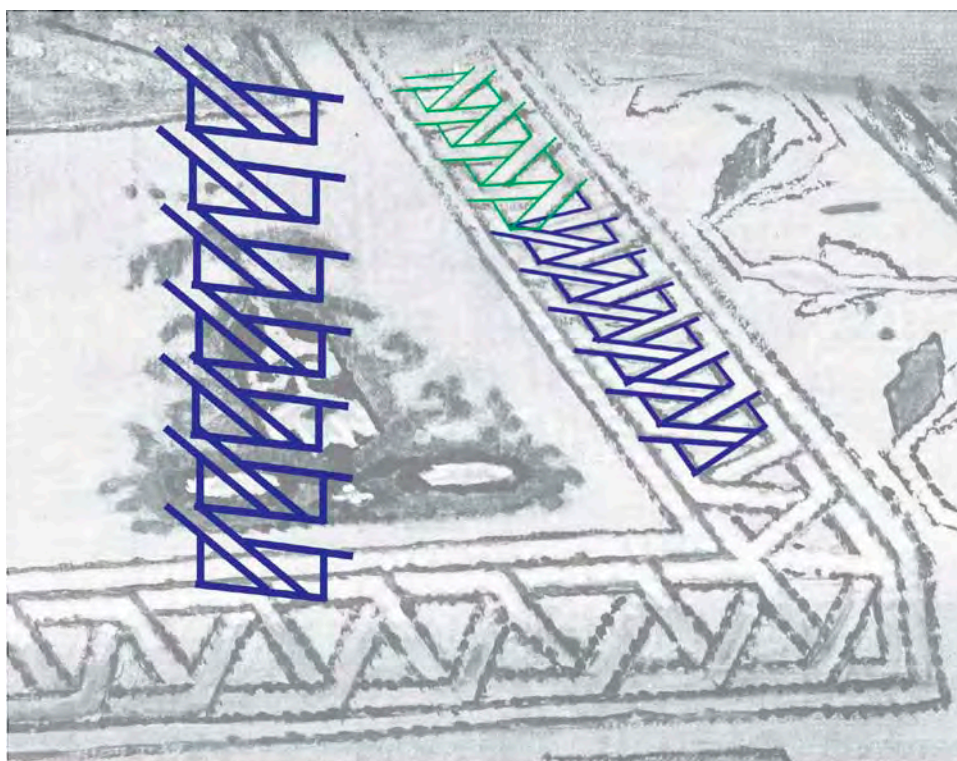


Figure 8. IR reflectogram of the border pattern of Figure 6. Overlay at left is seven segments of a repeating structure. When corrected for perspective, this is seen to be an excellent fit to the pattern at the front of the table covering. Changing the perspective, as happens when a lens is moved to refocus, gives an excellent fit to the pattern at the back. The maximum deviation of the perfect repeating structure from the pattern on the painting is 2 mm.

2.2 High Dynamic Range imaging (HDR) for revealing texture

Although the dynamic range of the IR reflected from these paintings is within the range that the camera's sensor is able to capture, it still can be very useful to employ High Dynamic Range (HDR) techniques and software.²⁰ Figure 9 is a reflectogram created by using HDR software²¹ to process three IR images made using three sets of exposures. It is beyond the scope of the present paper to describe the details of HDR processing of digital images, but note that using

appropriate HDR parameters it was possible to enhance the local contrast of the image to make visible the structure in the canvas of this painting.

2.4 Other Capabilities

Although no examples are provided here, this camera is also useful for extracting valuable information from three-dimensional cultural artifacts and works of art. Also, it is also useful for IR photomicroscopy.²²

3. DISCUSSION

The IR-modified camera discussed here does not cover the full range of wavelengths possible with a specialized camera that uses a sensor other than silicon,⁸ and does not produce the ideal quality that would be possible if a painting were examined under conditions of uniform lighting. However, as the examples in this manuscript show, its high resolution, low cost, portability, and ease of use by non-specialists represents a significant advance over what has been possible prior to this. Such a modified commercial digital camera for the first time makes it possible for any museum to capture high resolution IR reflectograms of their entire collection *in situ* without significant expenditure of staff time, and without disrupting the exhibition requirements of the institution.²³ In cases where analysis of an IR reflectogram revealed significant features, the new information would help curators decide if certain paintings warranted further detailed study by other scientific techniques.



Figure 9. High Dynamic Range (HDR) IR reflectogram of a detail of Figure 6, created using three IR images made at different exposures.

The 1100 nm upper limit of sensitivity means some features in some paintings cannot be imaged with this camera, because not all pigments are semi-transparent in this wavelength range. However, only a small percentage of paintings in museums ever have been studied in the IR,⁶ which means that currently no information at all is known about them from this technique. As the Lotto example illustrates, important information that otherwise simply would not be known can be revealed in IR reflectograms acquired *in situ* with this portable imaging system, at an average time of less than a few minutes per painting.²³

4. CONCLUSIONS

An inexpensive, highly portable, imaging system based on a modified digital camera has been developed that allows non-specialists to obtain high resolution IR reflectograms of works of art *in situ*. The capabilities of this system were illustrated with several examples, including one that confirmed and extended conclusions about how optical projections were used by a specific artist in the 16th century.

ACKNOWLEDGMENTS

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 - [10] Youn, Sunbin, Kim, Youjin, Lee, Jungbeom and Har, Donghwan, "A study on infrared reflectography for underdrawing detection using a digital camera," in *Proceedings of the IASTED International Conference on Internet and Multimedia System and Applications to Visual Communications* (IASTED, 128, (2008).
 - [11] Most lenses suitable for this work lack distance markings between 3 m and ∞ , requiring the operator to estimate where to position the lens for a desired focus distance, and rely on depth of field to compensate for the inevitable inaccuracy of the setting.
 - [12] Canon, Inc. 30-2, Shimomaruko 3-chome, Ohta-ku, Tokyo 146-8501, Japan.
 - [13] A more recent model, the 40D, uses the same CMOS technology, but with 11% greater linear resolution. However, since operation in the IR depends on light being transmitted by the dyes used for the blue, green, and red filters, similar tests to those described in this paper would have to be conducted with this camera to be certain it actually would function for this purpose.
 - [14] Coastal Optical Systems makes a 60 mm focal length, f/4 lens that is apochromatic over the wavelength range 315–1100 nm. However, aside from its \$4500 cost, the relatively long focal length requires positioning the camera a distance from objects that can be prohibitively far in some museum environments.
 - [15] Adobe Systems Inc. 345 Park Avenue. San Jose, CA 95110-2704.
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- [20] See, for example, Freeman, Michael, [Mastering High Dynamic Range Photography], Amphoto, New York, (2008).
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- [22] After focusing in the visible, the microscope stage is lowered by an appropriate amount to bring the IR into focus on the focal plane of the camera. The necessary offset distance need only be determined once for each objective on a given microscope by making a series of exposures at different distances.
- [23] By using an ISO of 1600 I was able to capture IR reflectograms of approximately 50 paintings in Tokyo's National Museum of Western Art in under an hour without use of a tripod. Although the noise due to the high ISO reduced the resolution to ~1 mm, the longest exposure was 1/30 sec., resulting in minimal additional loss in resolution due to camera motion.