Feature Article

Digital Imaging for Documenting and Modeling the Visual Appearance of 19th Century Daguerreotypes

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An optical inspection technique is evaluated for documenting the overall condition and for mapping the extent of tarnish on the surface of 19th century Daguerreotypes. The technique exploits the unique optical properties of Daguerreotypes to distinguish between light absorption and scattering by the daguerreian image. Combined with a digital imaging system, the technique provides an efficient tool for documenting a Daguerreotype's condition, for determining the optimal treatment exposure in different areas of the image, for monitoring the treatment progress, and for forecasting the results of natural aging or attempts at restoration. Examples of optical inspection and computer simulation of the visual appearance of a Daguerreotype versus different restoration treatments are presented.

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Introduction

Daguerreotypes were the earliest form of photographs and were first introduced by Louis Daguerre in 1839. Millions of Daguerreotypes were produced between 1839 and 1860, before daguerreotyping was replaced by more advanced photographic technology. Significant numbers of Daguerreotypes have survived to the 21st century and have invaluable historic, cultural, and artistic significance. Unfortunately, with the passage of time, the silver-based images tarnish and degrade. The restoration of 19th century Daguerreotypes is a risky procedure using any of the known cleaning techniques. Concerns about the possibility of harming a unique historic image in the process of restoration has stimulated the search for new techniques to remove tarnish under controllable and reproducible experimental conditions.

A comprehensive description of the art and science of Daguerreotypes may be found in the book by Barger and White.[1] Galvano-chemical, electrochemical, plasma reduction, and laser cleaning have been introduced in recent years.[2–6] These techniques provided different levels of success depending on the condition of the Daguerreotype and the type of tarnish to be treated. To provide a conservator with the option to choose the treatment that is most appropriate to the particular case, an efficient diagnostics technique is essential. A variety of physical diagnostic methods have been applied for characterizing Daguerreotypes including optical goniometry, optical and electron microscopy, x-ray spectroscopy, ultraviolet excited fluorescence, and laser mass spectroscopy.[7–11] Computer imaging techniques might be particularly beneficial, both for documentation and for diagnostics of the Daguerreotype's condition. In the previous work of Arney and Maurer,[12] the Daguerreotype plates were analyzed by a two-dimensional segmentation process based on the experimental observation of specific optical characteristics of healthy and tarnished areas of the plate. Diagnostics data were produced in which healthy and degraded pixels were classified and displayed.

In the present work, we further explore the unique optical properties of Daguerreotypes and introduce an alternative technique to characterize and document the condition of the surface. More specifically, we propose to use two independent images of a Daguerreotype, i.e., the positive and negative images, or positive and "compensated" images, as described below, for capturing a set of data which gives a more complete representation of the Daguerreotype plate. As will be shown, the set of two images then can be used for mapping tarnish, for enhancing the image, for forecasting the natural aging process, and for planing restoration treatments.

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Color Plates 1 through 5 are printed in the color plate section of this issue, pp. 53–54.

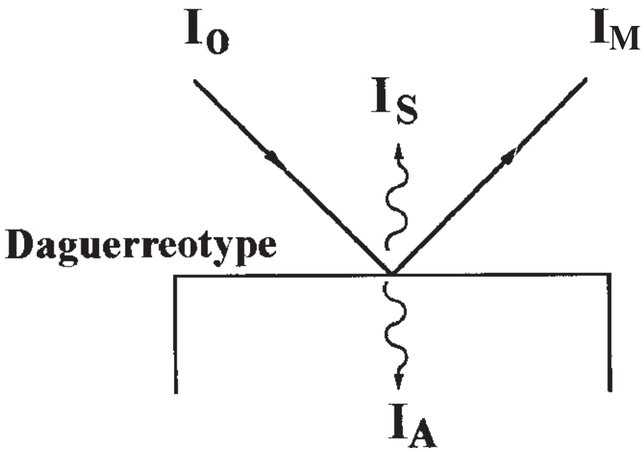

Figure 1. Schematic of the energy balance of light specular and diffuse reflected, and absorbed on a Daguerreotype surface.

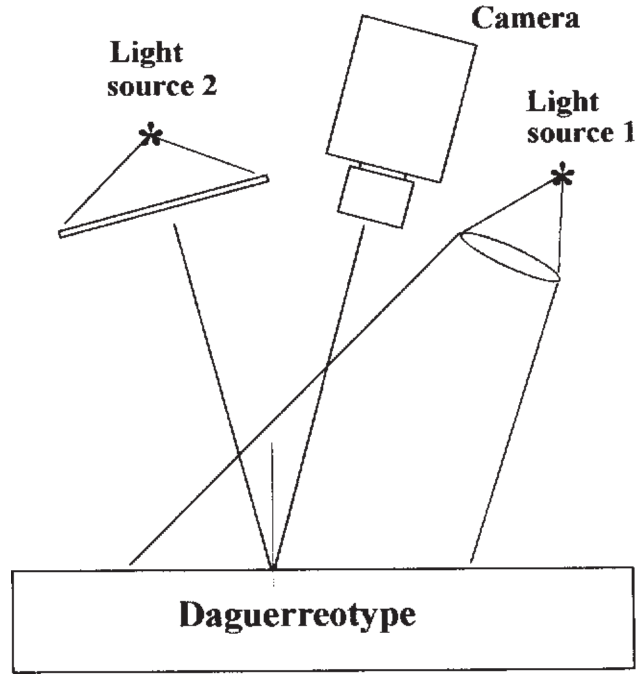

Figure 2. Experimental setup for capturing positive and negative images of a Daguerreotype. Source 1 provides a collimated light beam such that only the scattered light component can be viewed by a camera or observer. Illumination of the Daguerreotype by Source 1 produces a positive image. Source 2 is a white screen placed in a position where its reflection by a Daguerreotype plate can be viewed by the camera or observer. Therefore, Source 2 creates a negative image of the Daguerreotype.

Optics of a Daguerreotype Surface

An important fact of Daguerreotype optics is that the photo image is formed by light scattered by image particles and reflected from the polished silver background rather than being due to the absorption of light on the surface.[1,6] By changing the viewing and illumination angle of the Daguerreotype, the visual pattern can be observed as either a positive or negative image. The nature of this phenomenon can be explained by considering the specular and diffuse reflected components of the light from a Daguerreotype surface as shown in Fig. 1. The balance of energy associated with the diffuse reflected component, I_S, the specular reflected component, I_M, and the energy absorbed on the surface, I_A, can be formulated in a straightforward way:

$$I_o = I_S + I_M + I_A \quad (1)$$

where I_o is the irradiance created on the surface by the external light source, I_S is the diffuse energy flow from a unit area of the surface emitted into entire 2π angle, I_M is the specular energy flow from a unit area of the surface, and I_A is the energy flow absorbed by a unit area of the surface. Appendix I presents a more detailed consideration of the energy balance on a Daguerreotype surface. If the absorption component on the surface is negligible compared with the specular reflected and diffuse components, then by introducing fractions for energy flows defined as $f_S = I_S/I_o$, $f_M = I_M/I_o$, and $f_A = I_A/I_o$ we can rewrite Eq. 1 as follows.

$$f_S = 1 - f_M \quad (2)$$

The relationship between specular and diffuse components given by Eq. 2 explains the nature of positive and negative images of a Daguerreotype. If a Daguerreotype is viewed in a “scattered light” mode, it appears as a positive image. When observed in a “specular light” mode, the same Daguerreotype appears as a negative pattern. Figure 2 shows an experimental arrangement for capturing positive and negative images of a Daguerreotype. The image is observed by a camera at an angle close to 90 degrees to the plane of the Daguerreotype. The Daguerreotype can be illuminated by one of two light sources. The first light source, S_1, produces a collimated light beam and illuminates the surface such that the reflected light does not come to the camera. Because only scattered light can be captured, this scheme of illumination produces a positive view of the Daguerreotype. The second light source, S_2, is a white screen placed in the position where its reflection can be viewed by a camera from the Daguerreotype surface. This arrangement enables the camera to capture negative images of the Daguerreotype. **Color Plate 1a and 1b (p. 53)** show an example of positive and negative images of a Daguerreotype captured using the experimental setup shown in Fig. 2.

Returning to Eq. 1, we now consider the case when the absorption component, I_A, is not negligible. This occurs, for instance, when colored tarnish is presented on the surface. Because all three components of the Daguerreotype image I_S, I_M, and I_A are linearly related, one of the components can be found when two other components are known. We are particularly interested in mapping absorption on the Daguerreotype surface I_A using positive and negative Daguerreotype images. From the Eq. 1 and Eq. 2:

$$1 - f_A = f_S + f_M \quad (3)$$

where $(1 - f_A)$ is a negative representation of the absorption pattern, f_S and f_M represent positive and negative images respectively. From Eq. 3, it follows that the absorption pattern on the Daguerreotype surface can be mapped by calculating the sum of the positive and negative images.

The sum of these two images can be directly acquired using the experimental setup shown in Fig. 2. Indeed, if a Daguerreotype is illuminated by both light sources S_1 and S_2 and the intensity of light from the sources is properly adjusted, then the image formed in the focal plane of the camera is the sum of both positive and negative images. **Color Plate 1C (p. 53)** shows such an image captured when the Daguerreotype was illuminated by the two light sources simultaneously. Additional details of the experimental arrangement are presented in Appendix II. The intensity of the light from Source 1 was adjusted to compensate the image while the intensity of light from Source 2 was kept at a constant level. As can be seen from the figure, in the healthy central area of the Daguerreotype, the image can be almost completely compensated, while the tarnish pattern in the peripheral region stays clearly visible, independent of the relative intensity of the sources S_1 and S_2. We have conducted a systematic investigation of this phenomenon with several modern and 19th century Daguerreotypes and, in each case, have found that images from healthy Daguerreotypes can be efficiently compensated by using the illumination technique depicted in Fig. 2. We believe that the foundation for this observation is that the optical absorption of the image particles and the polished silver surface are very close and therefore the optical absorption usually does not play any significant role in the image formation in the healthy area of a Daguerreotype.

The technique of using two light sources for inspection provides a simple and efficient way for mapping any light absorbing tarnish on the surface. Different type of contaminants potentially can be identified based on their visual appearance. The most common types of contaminants observed are brownish tarnish uniformly distributed over the Daguerreotype plate and bluish films similar to those that appear in the central and peripheral region of the Daguerreotype in **Color Plate 1 (p. 53)**.

Although there are many ways that a surface map of tarnish could be used for forecasting and monitoring a Daguerreotype restoration, in this work we particularly focus on computer simulation of the visual appearance of a Daguerreotype versus aging, i.e., both backward and forward in time, and for forecasting the results of restoration versus the type of treatment.

Computer Simulation of a Daguerreotype Image

The accurate computer modeling of a Daguerreotype's visual appearance requires precise reproduction of it's color palette. When considering the Daguerreotype's color space, we have to keep in mind that the image of a healthy non-retouched Daguerreotype is formed by light scattered on micrometer-size image particles.[1] If no light absorbing species are presented on the Daguerreotype's surface, the efficiency of scattering does not depend significantly on the light wavelength. Such Daguerreotypes appear non-colored, i.e., essentially black-and-white image. In reality, however, the 19th century Daguerreotypes often carry colors due to tarnish on their surface or as a result of "solarization" in some parts of the image. Solarization, usually associated with overexposure, can result in a blue cast, especially in the highlight regions.[1] The portrait of **Color Plate 2 (p. 53)** shows an example of the color palette of positive and compensated images of a 19th century Daguerreotype. On both positive and compensated images a bluish halo appeared in the peripheral area of the image and the compensated image revealed an island-type pattern on the surface composed of areas covered or not-covered by a uniform brownish film. In the areas where the surface is not covered by the brownish film, the Daguerreotype appeared as a black-and-white image.

Because reproduction of colors is very important for an adequate representation of a Daguerreotype's appearance, we introduce a model that considers separately the intensity of red, green, and blue (RGB) components of light scattered or reflected by the Daguerreotype surface. Assuming the surface is covered by a tarnish film with thickness, h, the energy flow of the RGB components coming to a viewer can be written:

$$I_R = I_o\, \sigma(x,y) \exp(-2\alpha_R h) \quad (4)$$

$$I_G = I_o\, \sigma(x,y) \exp(-2\alpha_G h) \quad (5)$$

$$I_B = I_o\, \sigma(x,y) \exp(-2\alpha_B h) \quad (6)$$

where I_R, I_G, and I_B are the irradiance for the red, green, and blue components of the light coming to the viewer from a unit area of the Daguerreotype surface, I_o is the irradiance from the illumination source, α_R, α_B, and α_G are absorption coefficients of the tarnish film for red, green, and blue light components respectively, $h(x,y)$ is the tarnish film thickness in the (x,y) Daguerreotype plane, and $\sigma(x,y)$ is the density of the image particles on the Daguerreotype surface. Obviously, if $h = 0$, i.e., in the absence of the tarnish film, we have $I_R = I_G = I_B$ and the Daguerreotype appears as a black-and-white image. The factor of 2 in the Eqs. 4 through 6 takes into account that the light passes through the tarnish film twice, i.e., when coming to the surface and when it is reflected/scattered back from the surface.

Equations similar to Eqs. 4 through 6 can be written for the compensated Daguerreotype image. Because the compensated image originated by a sum of two components, one of which is proportional to $\sigma(x,y)$, and another is proportional to $(1 - \sigma(x,y))$, the final expressions are free of $\sigma(x,y)$:

$$I_R' = I_o \exp(-2\alpha_R h) \quad (7)$$

$$I_G' = I_o \exp(-2\alpha_G h) \quad (8)$$

$$I_B' = I_o \exp(-2\alpha_B h) \quad (9)$$

where I_R', I_G', and I_B' are the irradiance for red, green, and blue components of the compensated image respectively.

Increasing or reducing the tarnish thickness, $h(x,y)$, in Eqs. 4 through 6 can be used for modeling the Daguerreotype's visual appearance in the future or in the past time frame, respectively. To illustrate this we assume the thickness of the tarnish film is growing with a constant rate in each spot on the Daguerreotype surface, although the rate can be varied from spot to spot as shown in Fig. 3. By using the fact the Daguerreotype was produced around the year 1860, i.e., it is about 140 years old, we can expect, for example, that 70 years ago the tarnish film was half as thick as it is at the present time. We can use Eqs. 4 through 9 as a framework for modeling the appearance of the tarnish in the image. Indeed, substituting Eqs. 7 through 9 we can find:

$$I_R'' = I_R\, (I_R')^\theta \quad (10)$$

$$I_G'' = I_G\, (I_G')^\theta \quad (11)$$

$$I_B'' = I_B\, (I_B')^\theta \quad (12)$$

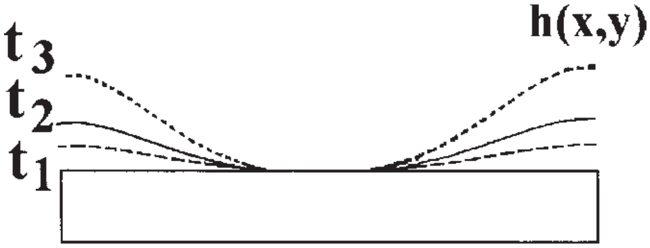

Figure 3. Growth of tarnish film on a Daguerreotype surface.

where I_R'', I_G'', and I_B'' are the color components of the image which represent the Daguerreotype in the past or future, and θ is the modeling parameter which defines the time factor. For example, $\theta = 0$ gives the appearance at the present time, $\theta = -0.5$ corresponds to the image with the tarnish half as thick, i.e., as it might appear about 70 years ago, and $\theta = 0.5$ forecasts the Daguerreotypes appearance 70 years from now assuming the same rate of tarnish formation in each spot on the surface as in the previous years. The result of modeling of the original Daguerreotype shown in **Color Plate 2A (p. 53)** is presented in **Color Plate 3 (p. 54)**. **Color Plate 3A** shows the image projected to 70 years back in time (less tarnish on the surface), **Color Plate 3B** shows the present image, and **Color Plate 3C** represents a forecast of the appearance of the Daguerreotype 70 years in the future (more tarnish on the surface). We would like to emphasize here, that the model given by Eqs. 9 through 12 takes into consideration the possible variation in the rate of the tarnish growth versus the location of the spot on the Daguerreotype surface. The experimental set of data for this consideration, in fact, is provided by the compensated image.

Modeling of a Daguerreotype Restoration

The model given by Eqs. 4 through 12 can be generalized to introduce the effects that result from restoration of a Daguerreotype. Although different processes can be used for restoration, for example, electrochemical or laser cleaning, the common feature of almost any of the restoration processes is that a desirable reduction of the tarnish is always accompanied by non-desirable degradation of the image due to removing image particles and creating light scattering micro-defects on the polished silver surface. The micro-defects increase the scattering background and therefore reduce the image contrast. **Color Plate 4B (p. 54)** shows an example of laser cleaning of a 19th century Daguerreotype. The left side of the image has been treated by the laser while the right side was kept untreated for reference. Although a significant reduction in tarnish is quite obvious, in the peripheral region of the cleaned area one can note the non-desirable effect of reducing image contrast and the disappearance of image details.

Effects associated with Daguerreotype restoration can be added into the Eqs. 4 through 12 by introducing a phenomenological factor $\exp(-\varepsilon\phi)$ which represents the restoration treatment. Here ϕ characterizes the treatment exposure, and ε is the “efficiency” of the treatment. The choice of the factor $\exp(-\varepsilon\phi)$ might be reasonable, particularly for describing chemical reactions on the surface or for laser removal of materials from the surface. The positive effect of restoration coming from a reduction of the thickness of the tarnish film, h is given as:

$$h' = h \exp(-\varepsilon\phi) \tag{13}$$

Any non-desirable effect of removing image particles that occur during restoration then can be presented by:

$$\sigma'(x,y) = \sigma(x,y) \exp(-\eta\phi) \tag{14}$$

where η is the efficiency of this process, which might be different from the efficiency of the tarnish removal ε, and ϕ is the treatment exposure (for example, exposure time) which is the same both for Eqs. 13 and 14. The formation of micro-damage on the Daguerreotype surface might be described by the density of light scattering defects on the surface versus the treatment exposure as follows:

$$\sigma_{\mathrm{Def}}'(x,y) = \sigma_{\mathrm{Def}}(1 - \exp(-\eta\phi)) \tag{15}$$

As one can expect, in this form the term corresponds to no damage before restoration ($\phi = 0$). As the treatment exposure is increased, the density of defects reaches the maximum value σ_{Def}. By combining Eqs. 1 through 4 and Eqs. 13 through 15 we can find for the color components of a Daguerreotype image after restoration:

$$I_R'' = I_R (I_R')^{\Theta}\, \Theta_2 + I_O(1 - \Theta_2) \tag{16}$$

$$I_G'' = I_G (I_G')^{\Theta}\, \Theta_2 + I_O(1 - \Theta_2) \tag{17}$$

$$I_B'' = I_B (I_B')^{\Theta}\, \Theta_2 + I_O(1 - \Theta_2) \tag{18}$$

$$\Theta = \exp(-\varepsilon\phi) \tag{19}$$

$$\Theta_2 = \exp(-\eta\phi) \tag{20}$$

where $I''_{R,G,B}$ are the R,G,B-components of the image after restoration, $I_{R,G,B}$ are the R,G,B-color components of the positive image before restoration, and $I'_{R,G,B}$ are color components of the compensated image of the Daguerreotype before restoration. The ratio of ε/η is the characteristic of the restoration process such as chemical or laser cleaning, mechanical polishing and etc. The bigger the parameter ε/η, the better the performance of the restoration process for removing tarnish without producing non-desirable effects. Now let us consider how the set of Equations 16 through 20 can be applied for the simulation of a Daguerreotype restoration.

Example 1:
Abrasive Cleaning

Let us consider the hypothetical mechanical polishing as a possible restoration treatment for the Daguerreotype shown in **Color Plate 2 (p. 53)**. This example is purely for discussion purposes, as abrasive cleaning can not be recommended for any serious attempt at cleaning Daguerreotypes. For such mechanical polishing we can assume $\varepsilon = \eta$ because the surface treatment is equally effective for removing tarnish and for removing image particles. By choosing the exposure, such that $\exp(-\varepsilon\phi) = 0.5$, i.e., the Daguerreotype is treated to reduce the thickness of the tarnish film by 50%, we can find the visual appearance of the Daguerreotype after treatment as shown in **Color Plate 5B (p. 54)**. Although the reduction of the tarnish is noticeable, the reduction of the image contrast is also very significant for this type of restoration.

Example 2
Laser Cleaning

Electrochemical or laser cleaning is another example of a restoration process that, in contrast to the mechanical polishing, can be characterized by a high efficiency for removal of tarnish and by a low yield of non-desirable effects such as the removal of image particles or the production of light scattering defects (see example of actual laser cleaning in **Color Plate 4, p. 54**). To apply the model given by Eqs. 16 through 20 to laser cleaning, we can assume $\varepsilon >> \eta$, and, to be more specific, we can take $\eta = 0.1\ \varepsilon$. Then, by using a treatment exposure that corresponds to reducing the tarnish thickness by a factor of two, i.e., $\exp(-\varepsilon\phi) = 0.5$, we can find the image appearance after the treatment. The result of such a calculation is shown in **Color Plate 5C (p. 54)**. In this case, removing tarnish does not cause significant reduction of the image contrast and therefore should be considered as a more appropriate restoration procedure.

So far we have used quite arbitrary assumptions about the ratio of ε/η for different types of restoration techniques. Because of that, the results of the simulation in **Color Plate 5B** and **Color Plate 5C (p. 54)** should be considered as an illustration of the concept rather then the solid prediction of the results of a specific treatment. However, we believe as more systematic experimental data on Daguerreotype restoration becomes available, such computer simulation can evolve into a more robust methodology with the possibility of becoming a routine procedure in the restoration of valuable museum artifacts.

Conclusion

We have shown that a digital imaging system, combined with a technique for the illumination and capturing of Daguerreotype images as presented in this work, can be a very useful tool for the initial inspection and documentation of a Daguerreotype's condition before performing any restoration. The use of compensated images has provided a straightforward way of mapping tarnish and identifying other non-healthy area on the Daguerreotype surface. This information can be used in multiple ways for predicting the results of restoration, for determining treatment exposure in different areas of the Daguerreotype, and for monitoring the treatment progress.

The results of the computer model of aging and restoration presented in this work have a preliminary character. No systematic experimental data presently are available to verify the results of such computer modeling by comparing the Daguerreotype images captured over an extended period of time. However, such data, in principle, can become available by investigating rapid artificial aging of Daguerreotypes in a specially created physico-chemical environment. Such studies are presently being considered. In the future, the art of Daguerreotype restoration may be transformed into a more quantitative science and we believe the methodology presented in this work might be particularly helpful for curators and conservators working on the preservation and restoration of Daguerreotypes.

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Appendix I—Theoretical Details

A starting point in the consideration of Daguerreotype optics is the fact that the photo image is formed by light scattered by image particles and reflected from the polished silver substrate. The appearance of the Daguerreotype, either as a positive or negative image, can be explained by considering the specular and diffuse component of the light from a Daguerreotype surface as shown in Fig. 1. The balance of energy associated with the diffuse reflectance, F_S, the specular reflectance, F_M, and the energy absorbed on the surface, F_A, can be formulated in a straightforward way:

$$F_o = F_S + F_M + F_A \tag{1A}$$

where F_o is the incoming energy flow. We can express the energy flow components in Eq. 1 through the conventional radiometric terms such as irradiance, I, and scattering function $S(\varphi,\psi)$ of the media.[15] Indeed, in Eq. 1 the incoming energy flow, F_o, is equal to irradiance, I_o, created by an external light source on a Daguerreotype surface.

Light Absorbance Component, F_A

Energy is absorbed on a Daguerreotype surface due to either tarnish (i.e., light-absorbing contaminants on the Daguerreotype surface) or due to energy dissipation by the polished silver substrate. Absorption by the silver substrate can be ignored in our consideration because it is relatively low, typically about 6%, and, more importantly, because it is uniformly distributed over the surface and does not interfere with the visual appearance of the Daguerreotype. To characterize the optical properties of the tarnish film, we will use transmittance, $T(x,y)$, which represents the portion of the energy flow passed through the film at a given (x,y) location on a Daguerreotype surface. Because the light reflected or scattered on a Daguerreotype surface passes the tarnish film twice, i.e., on the way to and from the surface, for F_A we can write:

$$F_A = (1 - T^2)\, I_o \tag{2A}$$

Note that F_A is a function of (x,y) because it represents the two dimensional distribution of tarnish on the Daguerreotype surface.

Light Scattering Component, F_S

Goniometric, i.e., light scattering, properties of a Daguerreotype, can be characterized by a scattering function, $S(\varphi,\psi)$, which represents the portion of the diffuse energy flow propagating in (φ,ψ) direction to the surface. For scattering into all angles of a hemisphere, $S(\varphi,\psi)$ is normalized to 1:

$$\iint S(\varphi,\psi)\, d\varphi\, d\psi = 1 \tag{3A}$$

For a Lambertian type of diffuse scattering, $S(\varphi,\psi)$ does not depend on the scattering angle:

$$S_{Lamb} = 1/2\pi \tag{4A}$$

Because Daguerreotypes do not necessary follow the Lambertian model of scattering media, Eq. 4 might not be applicable to Daguerreotypes. However, we will assume that the same scattering function, $S(\varphi,\psi)$, can be used all over the surface of an individual Daguerreotype. This assumption is reasonable as long as the size distribution of image particle is the same for all parts of the Daguerreotype image. We also assume that the density of image particles, i.e., the number of image particles per unit area, is a function of the coordinate (x,y) on the Daguerreotype surface, thus representing a two dimensional image. It is convenient to introduce a parameter $D(x,y)$, which represents the coverage of the surface by image particles. For a relatively low density of image particles, as is usually the case for Daguerreotypes, $D(x,y)$ is directly proportional to the density of image particles. In the more general case, the value of $D(x,y)$ is limited between 0 and 1; $0 < D(x,y) < 1$. In the absence of image particles, $D = 0$, and the scattering reflectance vanishes. In the other limiting case of very high density of image particles, $D = 1$, and only scattering reflectance exists while the specular component is 0. For Daguerreotypes, in most cases $D << 1$. Now, taking into account that the absorbance by tarnish reduces the amplitude of the scattering component, the total energy flow F_S can be presented as follows:

$$F_S = I_o\,(1 - T^2)\,D \iint S(\varphi,\psi)\,d\varphi\,d\psi \tag{5A}$$

We can rewrite the equation for the balance of energy on a Daguerreotype surface by using fractions of energy flows: $f_S = F_S/I_o$, $f_A = F_A/I_o$, and $f_M = F_M/I_o$. Then,

$$(1 - T^2) + (1 - T^2)\,D \iint S(\varphi,\psi)\,d\varphi\,d\psi + f_M = 1 \tag{6A}$$

Note that in Eq. 6, $T(x,y)$, $D(x,y)$ and $f_M(x,y)$ are functions of (x,y) coordinates on the Daguerreotype surface.

Positive and Negative Image of the Daguerreotype

Now let us consider how the positive and negative image of the Daguerreotype is formed in terms of specular and scattering reflectance.

We will assume the image is captured using the experimental setup shown in Fig. 2. For simplicity, we will assume the image is captured at an angle close to 90 degrees to the plane of the Daguerreotype, although non-90 degree angles will not change any conclusions of our analysis. The Daguerreotype can be illuminated by one of two light sources S_1 and S_2. A white screen irradiated by a collimated light beam is used either as a source S_1 or S_2 as shown in the figure. The screen S_1, is located such that its specular reflection from the Daguerreotype surface can not be viewed by the camera. Because only scattered light can be captured from the source S_1, this scheme of illumination produces a positive view of the Daguerreotype. The irradiance in the focal plane of the camera, F_{Pos}, is given by:

$$F_{Pos} = I_o\,(1 - T^2)\,D\,S(0,0)\,\Delta\varphi\Delta\psi \tag{7A}$$

where $S(0,0)$ is the amplitude of the scattering function in the direction perpendicular to the Daguerreotype surface and $(\Delta\varphi \times \Delta\psi)$ is the viewing angle of the camera.

The screen of the second light source, S_2, is placed in the position where its specular reflection from the Daguerreotype surface can be viewed by a camera. This arrangement enables the camera to capture negative images of the Daguerreotype. The irradiance, F_{Neg}, in the focal plane includes the sum of scattered and specular components and is given by:

$$F_{Neg} = I_o\,(1 - T^2)\,D\,S(0,0)\Delta\varphi\Delta\psi + I_o\,(1 - T^2)\,S_{Scr}(0,0)\,\Delta\varphi\Delta\psi\,\{1 - (1 - T^2)\,D \iint S(\varphi,\psi)\,d\varphi\,d\psi\} \tag{8A}$$

where $S_{Scr}(t,f)$ is the scattering function of the screen used in source S_2. For Daguerreotypes usually $D << 1$, the scattered component in Eq. 8 is much smaller than the specular component, the Eq. 8 can be simplified:

$$F_{Neg} = I_o\,(1 - T^2)\,S_{Scr}(0,0)\Delta\varphi\,\Delta\psi\{1 - (1 - T^2)\,D \iint S(\varphi,\psi)\,d\varphi\,d\psi\} \tag{9A}$$

We will define fractions for positive and negative images as $f_{Neg} = F_{Neg}/I_o$ and $f_{Pos} = F_{Pos}/I_o$. Also, it is convenient to introduce a parameter, $\mu = S_{Scr}(0,0)/S(0,0)$, which gives the ratio of the amplitude of the scattering function of the illumination screen and Daguerreotype for an angle corresponding to the observation angle, which is (0,0) in our case. From Eq. 1, Eq. 7 and Eq. 9 and using definitions of $f_S = F_S/I_o$, $f_A = F_A/I_o$, and $f_M = F_M/I_o$ we have:

$$f_A + f_{Pos} + \mu\, f_{Neg} = 1 \tag{10A}$$

Note that the fractions in Eq. 10 are 2D functions of the coordinate (x,y) on the Daguerreotype surface. If the scattering characteristics of the illuminating screen of the source S_2 are identical to the scattering characteristics of the Daguerreotype, $S_{Scr}(0,0) = S(0,0)$, then we have $\mu = 1$. In the absence of absorption, $f_A = 0$, the relation between f_{Pos} and f_{Neg} becomes very straightforward:

$$f_{Neg} = 1 - f_{Pos} \tag{11A}$$

In the more general case, when absorbance is present on a Daguerreotype surface, the positive and negative image can be used for mapping f_A:

$$f_A = 1 - (f_{Pos} + f_{Neg}) \tag{12A}$$

Compensated Image

The sum of the positive and negative images can be captured using the experimental setup shown in Fig. 2 when both light sources S_1 and S_2 are used to illuminate the Daguerreotype. Indeed, the irradiance in the focal plane of the camera is the sum of the irradiance corresponding to the positive and negative image. If the irradiance from sources S_1 and S_2 are I_{S1} and I_{S2} respectively, then from Eq. 10 we have:

$$I_{S1} f_A + I_{S1} f_{Pos} + I_{S1}(\mu\, I_{S2}/I_{S1}) f_{Neg} = I_{S1} \tag{13A}$$

As one can see from Eq. 13, if the intensity of the sources S_1 and S_2 are adjusted such that $I_{S2}/I_{S1} = S(0,0)/S_{Scr}(0,0)$, then Eq. 13 can be rewritten as:

$$f_A + f_{Pos} + f_{Neg}' = 1 \tag{14A}$$

Note that f_{Neg}' here is not identical to the f_{Neg} in Eq. 10. In the absence of absorbance, $f_A = 0$, and we have: $f_{Pos} + f_{Neg}' = 1$. A practical implementation of this fact is that, in the absence of absorbance and with the intensity of sources S_1 and S_2 adjusted as was described above, the positive and negative images are completely compensated by each other. What is viewed by the camera is a uniformly illuminated surface of the Daguerreotype without any image. In the case where the surface has light absorbing spots, then what will be detected by the camera is the absorbance pattern which is unaffected by the daguerreian image.

Appendix II—Experimental Details

The basic experimental setup for capturing positive and negative images of a Daguerreotype is shown in Fig. 2. The surface of the Daguerreotype was observed at an angle of about 80 degrees. The first light source, S_1, produces a collimated light beam that illuminated the surface at an angle of about 70 degrees. In such an experimental arrangement, the specular reflected light does not come to the camera. The irradiance from the source can be adjusted by placing a set of neutral density filters in front of the illuminator's lamp (coarse adjustment) or by changing the voltage of the power supply (fine adjustment). We found that the use of neutral density filters for coarse adjustment helps to keep the same spectral composition of the illuminating light while the irradiance on the Daguerreotype surface can be adjusted over the range of more than 2 orders of magnitude. The source S_1 was used to capture positive image of a Daguerreotype.

The second light source, S_2, is a Lambertian type white screen placed in position where its reflection from the Daguerreotype surface can be captured by the camera. The screen was illuminated by a collimated light beam from the same type of illuminator used in the source S_1. However, the screen and illuminator of the source S_2 were arranged such that only light diffusely scattered by the screen and then reflected from a Daguerreotype surface can reach the camera. Such illumination enables the observer or camera to view the negative image of the Daguerreotype.

The Daguerreotype image was captured by an electronic camera (Sony, Model 758), digitized by a frame grabber (Visionics, CA) and saved by a computer. The system provided 24-bit color images with a size of 684x480 pixels. The camera was equipped with a 75 mm lens and a set of extender rings for adjusting the view field of the camera to the size of Daguerreotype to be captured.

Because images were captured for digital modeling of Daguerreotypes, a special precaution was made to calibrate the camera's tone transfer function and achieve a linear relation of the pixel value versus irradiance. All images were captured with a reference gray scale placed next to the Daguerreotype as shown in **Color Plate 1 (p. 53)**. The diffuse reflectance of the grades in the scale was calibrated in advance by using a set of known neutral density filters. We found that the diffuse reflectance of the grades shown in **Color Plate 1 (p. 53)** are 5%, 31%, 47%, 63%, and 78% respectively. The image of the gray scale was used to measure the tone transfer function separately for each color components of the image, i.e., for red, green, and blue pixels of the camera. Data then were used to compensate non-linearity of the CCD sensor and enabled significantly reduced artifacts in the computer processed images. For example, if the sensor's non-linearity was ignored, then the compensated image digitally generated from the positive and negative image of the healthy Daguerreotype still did show a trace of the original picture. The same area analyzed using two light sources has appeared as a completely compensated image. The same level of complete compensation can be obtained in the computer-generated image by making correction to the tone transfer function of the sensor.

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