

RESEARCH ARTICLE

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Optimizing compositional images of daguerreotype photographs using post processing methods

Jeffrey M. Davis¹ and Edward P. Vicenzi^{2*}

Abstract

Microfocused X-ray fluorescence imaging was used to examine two 19th century daguerreotypes. The distribution of Hg-bearing nanoparticles beneath the Au gilding layer gives rise to contrast in the photographs. The sum image for Au + Hg M line X-rays is therefore a compositional image that mimics daguerreotype photograph contrast. Because the thickness of the Au and Hg on the surface represents a small fraction of the X-ray activation depth, the resulting sum images are not of high quality and are dominated by Poisson noise. This is true even for long collection times up to multiple days in length. Achieving superior contrast resolution by increasing the duration of data collection further is impractical. In this study, a new image processing technique based upon the Haar-Fisz algorithm and wavelet theory was used to improve the image quality of compositional maps. The digitally processed images show a reduction in noise without a loss of spatial resolution over the length-scale of photographic features. The Haar-Fisz denoising algorithm decreased the contribution of the Poisson noise in compositional images. Multiple resolution analysis improved image quality further. Features within the portraits are uniformly more recognizable in the final processed images relative to the raw X-ray images. Intensity line profiles that traverse midtone, highlight and shadow regions of the daguerreotype reveal that spatial resolution is not degraded by the image processing routines. Improvement in image quality is quantified by comparing the relative variance of the raw and Haar-Fisz processed imagery. The use of a Haar-Fisz denoising transformation, coupled with multiple resolution analysis was found to improve the quality of low count X-ray images without impacting the spatial resolution at the scale of photograph features. The process can be implemented in freely available open-source software with a minimum of programming effort. Such digital post processing routines offset the need for longer acquisition times to achieve improved X-ray fluorescence image quality. Finally, because the Au + Hg map is insensitive to surface imperfections and tarnishing via atmospheric adsorption of sulfur, digitally processed images may be used to reconstruct photograph features in heavily disfigured daguerreotypes.

Keywords: Early photography, Image analysis, Image processing, Noise suppression, Spectrum imaging, XRF, X-ray imaging

Background

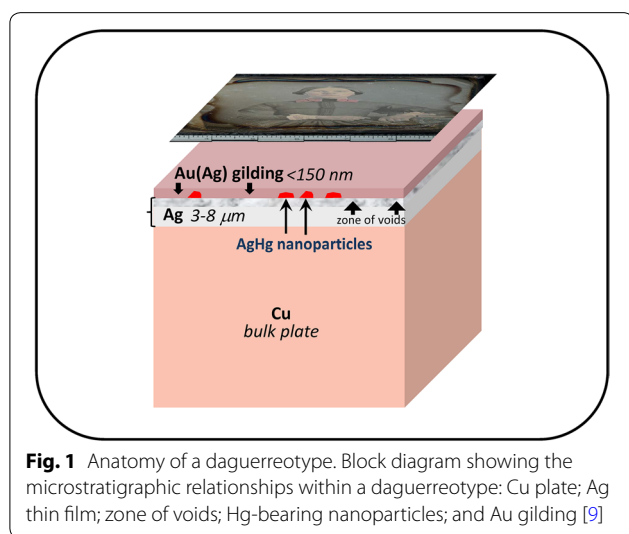
The invention of daguerreotype photography was made public at a meeting of the French Academy of Sciences in 1839. The first practical method to record the world in high fidelity, daguerreotype imagery transformed

disciplines in both the arts and sciences [1]. The multi-step process requires a Cu plate; (1) coated with Ag and polished to a mirror finish; (2) exposed to halogens; (3) exposed to light within the camera; (4) subjected to Hg vapors; (5) rinsed to remove remaining salts, and finally; (6) gilded with Au (Fig. 1). A physical model to explain the image contrast in daguerreotypes can be accounted for via diffuse reflectance of high density Hg-bearing nanoparticles in highlight regions, relative to specular reflectance in shadow regions that contain few image particles

*Correspondence: vicenzi@si.edu

² Smithsonian Institution, Museum Conservation Institute, 4210 Silver Hill Road, Suitland, MD 20746, USA

Full list of author information is available at the end of the article



[2, 3]. Many daguerreotypes have survived >170 years in reasonably good condition. Other 19th century images suffer from a variety of degradation mechanisms, including; Ag sulfide tarnish films of differing thicknesses characterized by interference colors; Cu accretions; microbial filaments; and silicate detritus from unstable cover glass [4]. Efforts to study specific alteration mechanisms have been made to understand both chemical [5] and biological [6] processes.

Examination of an entire daguerreotype plate, up to >350 cm², by optical imaging methods to document its condition is a useful endeavor [7]. Hyperspectral imaging of whole plates, particularly in the near infrared (NIR), has proven useful for discerning features obscured in visible wavelengths by Ag sulfide tarnish [8].

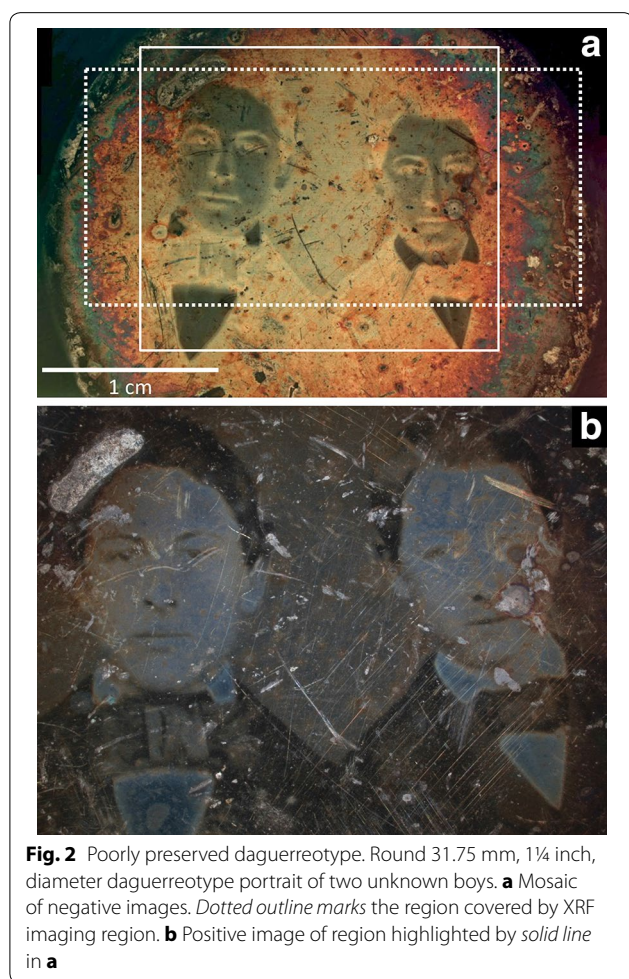
This study employs scanning microfocus X-ray fluorescence spectrometry (μ XRF) to reveal 2D elemental distributions of daguerreotype plates with X and Y dimensions on the scale of multi-centimeters. Chemical documentation at the object scale complements optical imagery, and in many cases, identifies/confirmes a degradation mechanism for any potential treatment. Because the information regarding the image and alteration products is encoded in the top ~100–200 nm of the plate [9, 10], and the primary x-ray signal penetrates many micrometers into the Ag coating and Cu bulk, the resultant chemical signal of interest is weak. Poor signal quality, on the order of less than 10 counts per second in the spectral region of interest (ROI), generally results in an unsatisfactorily noisy image [11]. In this case, the signal is dominated by the variance inherent to a Poisson distribution. The most commonly used strategy to reduce Poisson noise involves increasing the total number of counts in the signal. This is often accomplished by brute

force data collection methods, such as; (1) increasing the power of the X-ray source; or, (2) integrating the signal over a longer period of time [12]. However, because the photograph information is derived from a small mass, relative to the mass within the XRF activation volume of material, such data collection approaches are simply not efficient nor practical.

An alternative solution for improving image quality involves using image processing techniques, such as spatial binning of data over neighboring pixels, resulting in a smaller image with better statistics. Users of more advanced image processing software tools will also be familiar with techniques such as: (1) median filtering, where the statistics from eight neighboring pixels are used to reduce the noise of the image, or; (2) spline fitting, where a polynomial spline is fit to the image by rows or columns to reduce noise. These image processing techniques offer a useful trade-off of spatial resolution for improved noise characteristics over a local neighborhood of pixels. The aim of this effort is to provide an example of a data processing approach that produces improved image information quality from raw μ XRF imagery. This method relies on emerging concepts and data transformations being implemented in the signal processing community. Specifically, two methods will be considered: (1) The Haar-Fisz denoising transformation; and, (2) the Multiple Resolution Analysis method. The primary advantage of using these techniques is that they are able to improve the information quality of the data without sacrificing global spatial resolution. This is made possible through mathematical transformations that decouple the Poisson relationship between the intensity to noise ratio.

Methods

Two daguerreotypes portraits were chosen for examination in this study: (1) a poorly preserved 31.75 mm/1¼ “round daguerreotype of two unknown males that was likely part of a 19th century pocket watch (Fig. 2, hereafter two boys); (2) a well-preserved sixth plate, 69.9 × 82.6 mm/2¾ × 3¼”, of an unknown young woman (Fig. 3, hereafter Woman Sitting). Specimens were imaged in an EDAX Eagle III μ XRF. This system uses a polycapillary optic to focus the primary X-ray beam into an elliptical spot with a major axis diameter of approximately 50 μ m. Samples were affixed to an XY raster stage. At each point, a full X-ray spectrum, 2048 channels at 10 eV per channel, is recorded and stored in a binary X-ray spectrum database. From the database, multiple software packages have been used to interrogate the data [13, 14]. Because the Eagle III system uses a Si(Li) detector, count rates were limited to approximately 20,000 counts/s. Thus, the full power of the X-ray tube



was not exploited in order to prevent the detector from being paralyzed by dead times above 50 %. The X-ray data set for the Two Boys daguerreotype, was collected using a per-point integration time of 3 s, resulting in a total imaging time of approximately 116 h including instrument overhead. For the larger daguerreotype, Woman Sitting, an integration time of 1 s per point was used, resulting in a total acquisition time of approximately 64 h.

Au + Hg M_{α} sum images were transformed into a matrix in R, a freely available open source data analysis toolset [14], and processed using the {denoise.modwt.2d} function with the Haar wavelet selected as the analyzing wavelet. Numerous software packages, both open source and licensed software, are capable of performing the requisite image processing routines. The R package “waveslim” was selected owing to the simplicity of the analysis and the availability of suitable scripts [15]. Although the code is not speed or memory optimized, it can be used to process any X-ray compositional data set. Two algorithms were used to create the images in this study. The first algorithm executes the Haar-Fisz de-noising



algorithm [16], while the second algorithm performs a multiple resolution analysis [17].

The Haar-Fisz transformation

The Haar-Fisz (H-F) transform used here is a member of a class of transformations known as variance stabilization transforms (VST) [18]. These transforms are used to solve the problem at the root of all Poisson counting processes, specifically, that data variance scales with the number of counts. X-ray images are a two dimensional plot of the counts extracted from an X-ray region of interest, where high grayscale level pixels represent high counts/concentration of an element, and low grayscale level pixels represent correspondingly low counts/concentration of an element counts. The variance of the counts in each pixel in an X-ray image is equal to the number of counts in that pixel, and the standard deviation is the square root of the number of counts. It follows that the variance and standard deviation increase with the number of counts. This may seem counterintuitive, given that higher count images, collected with a longer dwell time per point, have lower noise resulting in higher quality images. Our perception of image quality is based upon a visual approximation of the ratio of the noise to the signal. Thus, a point with 10,000 counts will

have approximately 100 counts of noise, resulting in an n/s ratio of 0.01, or 1 %. For lower count images, such as the compositional images in this study, noise makes up a significantly larger fraction of the data. By decoupling the relationship between the variance and the number of counts, the primary constraint on image quality can be mitigated.

While this goal may seem unachievable without suffering an undesirable trade-off, it is part of a well-established group of mathematical transformations used in the field of signal processing termed wavelet theory [19, 20]. Noise removal and image reconstruction methods are imperfect tools, but the procedures markedly improve image quality and reduce the contribution of Poisson noise. Ultimately, the goal of the Haar-Fisz transform is to change the relationship between the counts and the variance to that of a Gaussian system, rather than a Poisson system. “Gaussianized” noise is not subject to the variance constraint of a random Poisson system.

The H-F transform is a two step process, beginning with a data transformation that noise-normalizes the counts. Once the data are transformed, a series of Haar wavelets are fit to the data. Haar wavelets can be efficiently implemented in software, and they are used to represent counts/intensity data, similar to a conventional statistical model. However, rather than a single function representing the data, numerous wavelets are fit to the data. These wavelets are sorted according to the noise component. The first wavelets fit to the data are smooth functions with almost no noise. Later wavelets contain successively more noise, and the final ones are almost exclusively noise. Adding all of the wavelets together results in a near-perfect reconstruction of the original image. However, the image can also be reconstructed by taking only a portion of the wavelets. In this study, only the first 75 % of the wavelets were used to reconstruct the image, and the result is an image with the noise components removed.

Multiple resolution analysis

The final step involves reprocessing the Haar-Fisz transformed data using the multiresolution analysis function (MRA). It is common in wavelet image analysis to use multiple algorithms, iterative algorithms and other combinations of image processing techniques. However, the process outlined above for the H-F transform is very similar to the process used for the MRA. This function is an example of a discrete wavelet transformation routine whose goal is to decompose an image into a certain number of wavelet functions. The functions are sorted with regard to spatial resolution, from an entire image to a single pixel [17]. Once again, a portion of the resulting wavelets are used to reconstruct the image. The noisy

components have resolutions of single pixels, while the non-noisy components have resolutions of multiple pixels. With both transformations, it is important to remember that, at some point, the wavelets are smoothing out real data and variation. The selection of which range of wavelets to use is left to the user.

Results

The most useful X-ray image for depicting daguerreotype features is comprised of Au and Hg M_α X-rays (Fig. 4). Though convolved, the Au + Hg sum image offers an advantage as spectral deconvolution at each pixel would impose a data processing time penalty. The original, unprocessed images, as well as the processed data are shown in Figs. 5 and 6. Observing the differences between the raw and H-F transformed images reveals the subtle, but noticeable change in the images. The H-F image exhibits lower noise and the high contrast features of the image have not been significantly degraded. The details in the collars and in the ties of the Two Boys image have been preserved. In *Woman Sitting*, there are several facial features that are more apparent in the Haar-Fisz image, and there was excellent preservation of the details in the fingers and the pleats of the dress.

The MRA solutions step has provided additional image contrast and feature improvement. Details within the collars and neck ties in the Two Boys are preserved, and several facial features, such as eyebrows and lip lines are more readily apparent. *Sitting Woman* MRA results are

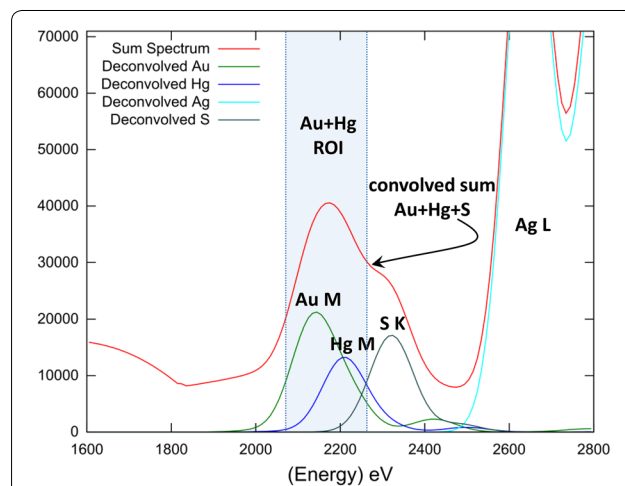
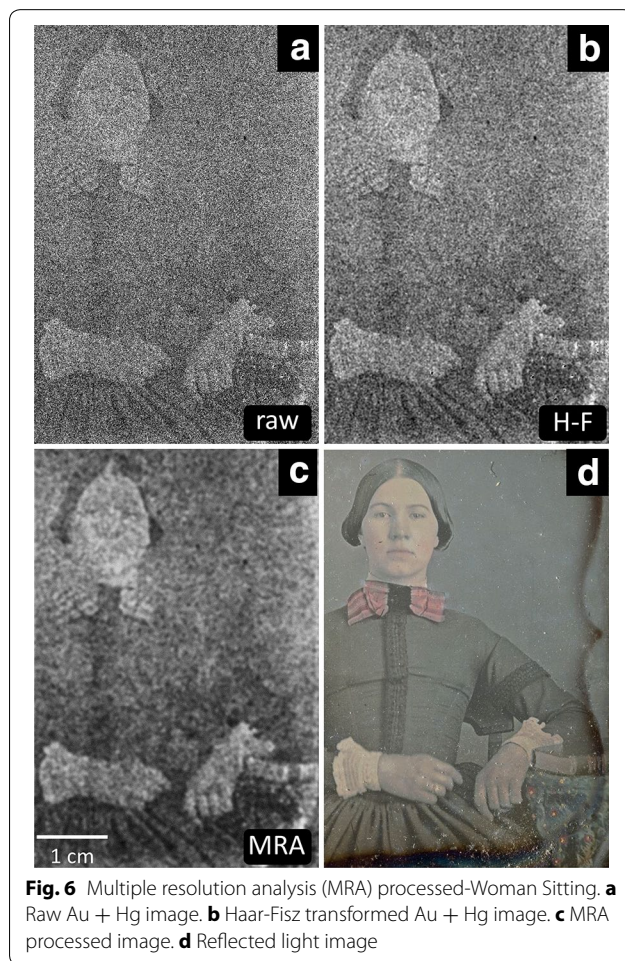


Fig. 4 X-ray fluorescence spectrum of a tarnished daguerreotype. Convolved X-ray peaks in the vicinity of 2200 eV: Au (2123 eV) from the gilding; Hg (2195 eV) from image nanoparticles; and S (2308 eV) from Ag sulfide tarnish. The shaded spectral region of interest ROI outlined by dotted lines represents the sum of Au + Hg M_α X-ray lines. Deconvoluted peaks: Au M_α (green); Hg M_α (blue); S K_α (dark green); and Ag L_α (cyan) shown beneath the convolved/sum spectrum (red)



more subtle, however the visibility of the features in the hands and book are easier to discern. When compared to the reflected light image, it is clear the MRA processed Au + Hg image is not sensitive to surface imperfections and atmospheric alteration (Fig. 5c, d).

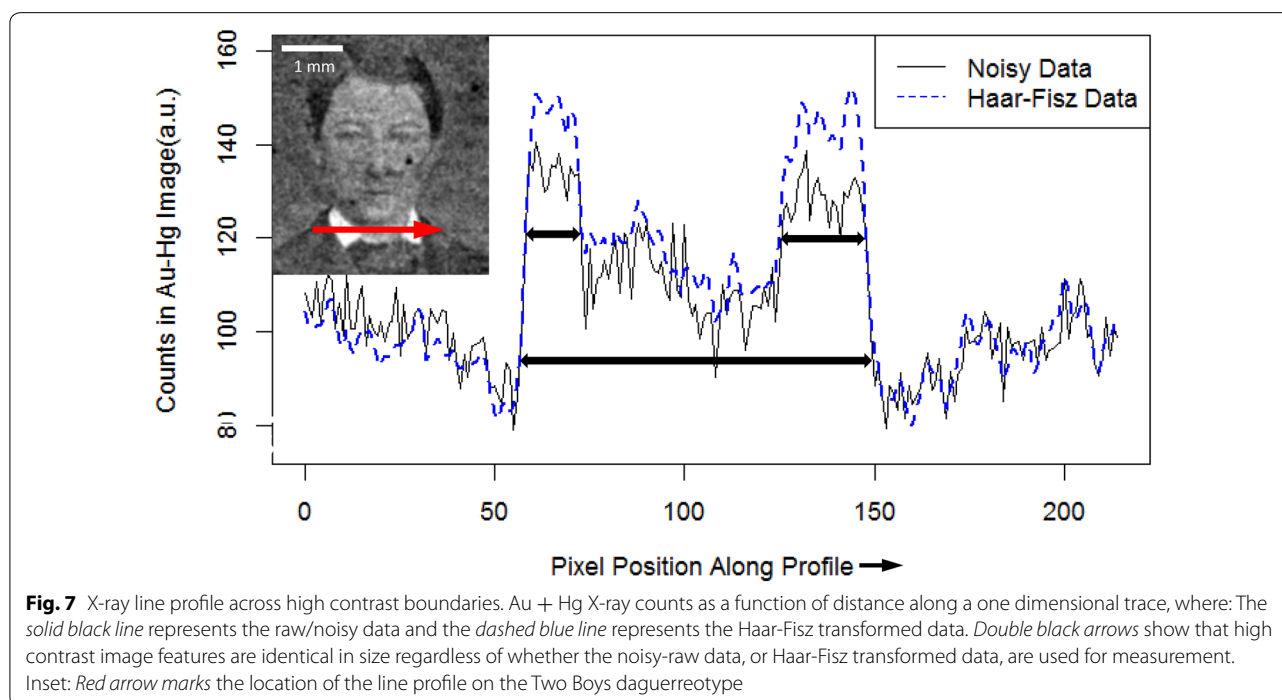
It may appear that the spatial resolution of the compositional image has been degraded by executing the VST routines, yet this is not the case. To demonstrate that spatial fidelity of the image has not been lost, a line trace was performed across a high contrast feature within the Two Boys plate. The profile crosses multiple contrast boundaries of multiple midtones and highlight regions of the photograph. Figure 7 shows the results of the line trace for the raw and H-F transformed images. Linear measurements of daguerreotype features taken



from either the raw data, or the transformed data, result in the same value. It should also be noted that the values from the collar were higher in the Haar-Fisz data. This is a common result of wavelet transformations, namely, an improvement in contrast of features in an image. There are other wavelet transformation methods that are designed to increase or improve contrast in images without increasing noise.

Discussion

Haar-Fisz VST image processing routines provide a noticeable improvement in noisy X-ray imagery. While spatial binning of data results in the local loss of data at the several pixel level, image quality is improved without impacting the spatial resolution of the features in the daguerreotype (Fig. 7). However, it should be noted that this transform only improves *spatial* information quality. The *spectral* data from which these images are derived, remains unaltered. In the absence of performing the image transforms, one would be faced with increasingly long integration times for a data collection approach to



achieve similar image quality to the results shown here. For example, an increase in dwell time by a factor of three would significantly increase the total frame time, and would only result in an improvement of approximately the square root of three in the noise of the image. For this reason the data processing approach was determined to be more desirable.

As a method of checking the conversion quality of the image, four regions on the Two Boys daguerreotype were selected for further analysis. These areas represent four gray scales ranges (Fig. 8). The rectangular region in each of the four areas contained approximately 1500 pixels. The mean and the variance of the pixels were calculated using Lispix [13]. These values were used to calculate the relative variance of each region, and those results are plotted in Fig. 8. The raw Au + Hg image, which is subject to Poisson counting statistics, should have a relative variance of approximately 1. The Haar-Fisz transformed data, no longer subject to the limitations of Poisson counting statistics, have a lower relative variance in those same regions.

An important distinction should be made between wavelet based VSTs and other image processing and filtering techniques. Wavelet based methods, like those used in this study, are based upon the concept of sparsity. Noise, which is the random fluctuation of the signal, is a non-sparse, or ubiquitous, component of every image. Image features, such as the shapes and forms in daguerreotype photographs that are recognizable are termed, sparse features; capable of being represented by a

series smooth functions. Unlike spline fitting, median filtering, or other digital filters, the purpose of the VST is to identify and discriminate between sparse and non-sparse features. As a result, they do not rely on local estimations of noise and signal, and as such, they improve the image without degrading spatial resolution of the image significantly. It should be noted that once transformed, the data can be passed through additional filters and image processing routines to further improve the information content. The two step process identified here can be implemented using a small number of lines of code (see Additional files 1, 2). Finally, the digitally processed compositional maps may be used to aid in the reconstruction of a heavily disfigured daguerreotypes given their insensitivity to Ag sulfide tarnish and other surface imperfections.

Conclusions

In cultural heritage research, the ability to collect large area images at high X-ray count rate is often limited by the nature of the object of interest. The specimen may be large, rough, heterogeneous, and structurally complex. Additionally, an object may be available for study within a strictly defined time frame. These constraints may limit information quality and impose practical collection time limitations on the measurement. Even when employing state-of-the-art X-ray detectors, it is impractical to collect X-ray image data over multiple days for most research groups given the demand on high cost instrumentation. The results of this study demonstrate

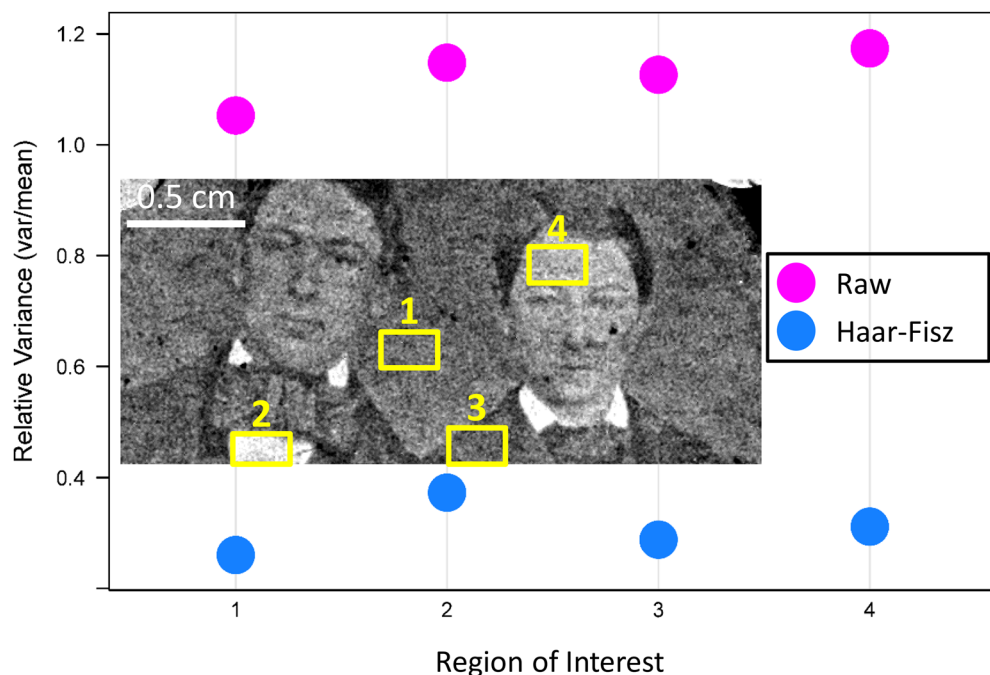


Fig. 8 Relative Variance of raw versus Haar-Fisz transformed images. The result of tracking the variance in four regions of the Two Boys image is shown. Inset: the Haar-Fisz transformed image is shown with *yellow rectangles* representing the areas sampled for computation. The data from the Haar-Fisz transformed image is shown as *blue dots*, and the data from the raw image is shown in *magenta*. Relative variance is represented by the variance divided by the mean

that alternatives to longer integration times for improving the information quality of X-ray images are available. Although the intensity of the X-ray signal was low, and the resulting Au + Hg daguerreotype images were of poor quality, Haar-Fisz data transformations improved image quality without sacrificing spatial resolution. The approach presented here represents a specific wavelet theory solution one can employ among many such solutions. As the tools and algorithms used to perform these procedures mature, the implementation barrier will decrease accordingly, making it easier for non-experts to take advantage of advancements in the field of digital image processing and analysis.

Additional files

Additional file 1. The original, unaltered Au-Hg M_0 image from the "Two Boys" daguerreotype saved as a .tif file.

Additional file 2. An example analysis script written in the R statistical programming environment that performs the Haar-Fisz and Multi Resolution Analysis transformations on the "Two Boys" daguerreotype image and then produces a plot similar to that shown in Fig. 5 of this paper. Users can download and use R for free at <http://cran.r-project.org>. The script file can be opened using any text editor such as notepad or notepad++. Comments and instructions for how to use the script are preceded by the "#" symbol. Users should read each comment, then copy the code from the text file into the RGui.

Abbreviations

H-F: Haar-Fisz transform; μ XRF: microfocus X-ray fluorescence spectrometry; MRA: multiple resolution analysis; ROI: region of interest; S/N, N/S: signal to noise ratio, noise to signal; VST: variance stabilization transforms; XRF: X-ray fluorescence spectrometry.

Authors' contributions

JMD collected X-ray image data, conducted all facets of image and data processing/statistical routines, and co-wrote the paper. EPV provided the specimens for the study, established X-ray imaging conditions with JMD, prepared figures, and co-wrote the paper. Both authors read and approved the final manuscript.

Authors' information

JMD is an application scientist with PNDetectors, GmbH and is an XRF spectroscopic imaging specialist. Before taking his current position he was a research engineer in the Materials Measurement Science Division at the National Institute of Standards and Technology in Gaithersburg, MD, USA. He is a director and member of the executive council of the Microanalysis Society. He has organized symposia on the topic of XRF imaging and analysis for the engineering and science communities. EPV is a research scientist who specializes in microanalysis at Smithsonian Institution's Museum Conservation Institute and President of the International Union of Microbeam Analysis Societies.

Author details

¹ PNDetector GmbH, Emil-Nolde-Str. 10, 81735 Munich, Germany. ² Smithsonian Institution, Museum Conservation Institute, 4210 Silver Hill Road, Suitland, MD 20746, USA.

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Competing interests

The authors declare that they have no competing interests.

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