Paper watermark imaging using electron and low energy x-ray radiography

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Abstract
Historians and librarians are interested in watermarks and mould surface patterns in historic papers, because they represent the “fingerprints” of antique papers. However, these features are usually covered or hidden by printing, writing or other media. Different techniques have been developed to extract the watermarks in the paper while avoiding interference from media on the paper. Beta radiography provides good results, but this method cannot be widely used because of radiation safety regulations and the long exposure times required due to weak isotope sources employed. In this work, two promising methods are compared which can be used to extract digital high-resolution images for paper watermarks and these are electron radiography and low energy X-ray radiography. For electron radiography a “sandwich” of a lead sheet, the paper object, and a film in a dark cassette, is formed and it is exposed at higher X-ray potentials (> 300 kV). The photoelectrons escaping from the lead sheet penetrate the paper and expose the film. After development, the film captures the watermark and mould surface pattern images for the paper being investigated. These images are then digitized using an X-ray film digitizer. The film employed could potentially be replaced by a special type of imaging plate with a very thin protection layer to directly generate digital images using computed radiography (CR). For the second method, a low energy X-ray source is used with the specimen paper placed on a digital detector array (DDA). This method directly generates a low energy digital radiography (DR) image. Both methods provide high quality images without interference from the printing media, and provide the potential to generate a “fingerprint” database for historical papers. There were nevertheless found to be differences in the images obtained using the two methods. The second method, using a low energy X-ray source, has the potential to be integrated in a portable device with a small footprint incorporating user safety requirements. Differences obtained using the two methods are shown and discussed.

Keywords
Radiography, Historians, Detector arrays, Nuclear safety, Leptons

Disciplines

Comments
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Paper Watermark Imaging using Electron and Low Energy X-ray Radiography

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\textbf{Abstract.} Historians and librarians are interested in watermarks and mould surface patterns in historic papers, because they represent the “fingerprints” of antique papers. However, these features are usually covered or hidden by printing, writing or other media. Different techniques have been developed to extract the watermarks in the paper while avoiding interference from media on the paper. Beta radiography provides good results, but this method cannot be widely used because of radiation safety regulations and the long exposure times required due to weak isotope sources employed. In this work, two promising methods are compared which can be used to extract digital high-resolution images for paper watermarks and these are electron radiography and low energy X-ray radiography. For electron radiography a “sandwich” of a lead sheet, the paper object, and a film in a dark cassette, is formed and it is exposed at higher X-ray potentials (\textgtrsim 300 kV). The photoelectrons escaping from the lead sheet penetrate the paper and expose the film. After development, the film captures the watermark and mould surface pattern images for the paper being investigated. These images are then digitized using an X-ray film digitizer. The film employed could potentially be replaced by a special type of imaging plate with a very thin protection layer to directly generate digital images using computed radiography (CR). For the second method, a low energy X-ray source is used with the specimen paper placed on a digital detector array (DDA). This method directly generates a low energy digital radiography (DR) image. Both methods provide high quality images without interference from the printing media, and provide the potential to generate a “fingerprint” database for historical papers. There were nevertheless found to be differences in the images obtained using the two methods. The second method, using a low energy X-ray source, has the potential to be integrated in a portable device with a small footprint incorporating user safety requirements. Differences obtained using the two methods are shown and discussed.

\textbf{INTRODUCTION}

During the long history of pre-industrial paper manufacturing, watermarks were embedded in paper by sewing wire designs onto the flat woven wire “mould” surface on which each sheet was made. The variation in local paper thickness caused by the wire watermark left the dry paper able to transmit light more readily in exact duplication of the wire watermark design. The mould surface itself also imparted subtle patterns into the paper during sheet forming as shown in Figure 1. Such features are usually visible when looking through the paper held up against a light source. These paper watermarks and mould surface patterns provide important information for historians, librarians and other book specialists\cite{1}. The research community is endeavoring to digitize historic paper watermarks and create a database to first log, and then enable searching and dating of particular signatures which can then be compared with unknown samples to give identification and dating with high accuracy and easy accessibility \cite{2, 3}.

Paper watermarks and mould surface patterns are usually hidden beneath hand-written/printing inks or other media. Researchers have explored different techniques to extract watermarks from various paper types \cite{4}. Tracings and rubbings are the easiest and most cost-effective methods, but they are non-digital and result in characterizations
with poor image details. Optical methods are safe and fast, and researchers have developed transmitted light photographs (back-lighting) which are used to acquire digital images of paper watermarks. However, it is difficult to achieve clean removal of residuals (shadows) resulting from hand-written or printing media using these methods. Al Hiary developed some digital image processing algorithms to extract paper watermarks, and had success in a limited number of situations [5]. Researchers have also developed phosphorescence techniques and UV-photography to extract paper watermarks, but they found that these techniques require consumable supplies and the results then need extra effort to fully digitalize the final images. Some researchers have experimented with thermography for watermark extraction, but curators of rare books and paper conservators have reservations about the safety of exposing historical papers to the necessary heat source.

**FIGURE 1.** Examples of (a) a Mould Used in Making Paper by Hand, and (b) Watermark and Mould Surface Pattern in a Historical Paper seen Viewed Using Transmitted Light. (Photo Credit: T. Barrett)

Radiography is a promising technique for watermark extraction, providing the best image qualities when the various available methods are compared. In looking at radiography there is more than one implementation. There are three types of radiography that can be used for paper signature measurements: beta radiography, soft X-ray (low energy X-ray) radiography and electron radiography. Beta radiography gives good image quality its use is limited due to the need for safety requirement when working with beta source isotopes. In looking at options, Rakvin et al. validated the feasibility of using computed radiography (CR) for watermark extraction and paper structure characterization [6].

There remains however a need for a low-cost and safe, method for high quality watermark image extraction, with only limited requirements for infrastructure and equipment, and which has the potential to be deployed in libraries for on-site scans. In this paper preliminary results obtained using electron and low energy X-ray radiography are presented.

**METHODS**

**Electron Radiography**

In order to set up an experiment for electron radiography, a film cassette was used to bundle three layers into a “sandwich” as shown in Figure 2. The paper sample is set between 0.025-0.1mm thick lead foil and film. The film could be replaced by a computed radiography (CR) imaging plate (IP) to directly acquire digital images. The incoming X-ray beam is generated at 300-420kVp, with a 2.5-5 cm steel pre-filter, hardening the beam. The
phenomena that occurs uses the photoelectric effect [7], where X-ray photons interact with the lead foil, which emits electrons, and the electrons penetrate the paper, exposing the film or a CR IP. When considering options for detectors it should be noted that digital detector arrays (DDA) usually have a thick protection input screen, which act as a shield for the electrons. Therefore, DDAs are not suitable for this application.


Low Energy X-ray Radiography

The low energy X-ray radiography experiment employed the simple set up as shown in Figure 3. The X-ray source with a beryllium (Be) window was limited to 25kVp-30kVp without filters, so that the setup is sensitive for minimal changes in paper thickness. In the current work, two types of digital detectors were used and these were a digital detector array (DDA) and a computed radiography (CR) imaging plate (IP).

Detectors and Scanners

For the electron radiography Fuji XI 100 films and Fuji UR 1 imaging plates were used. For the low energy X-ray radiography Duerr UH imaging plates and a Perkin Elmer 2923NDT DDA were employed as shown in Figure 4(a). A Duerr CR scanner type HD-CR 35 NDT (Figure 4(b)) was used to read the imaging plates.

![Image of X-ray equipment](image1.png)

(a) Perkin Elmer 2923NDT DDA. (b) Duerr CR Scanner HD-CR 35 NDT.

**FIGURE 4.** X-ray Equipment (a) Perkin Elmer 2923NDT DDA. (b) Duerr CR Scanner HD-CR 35 NDT.

![Image of currency with watermarks](image2.png)

**FIGURE 5.** Examples of Currency Showing Watermarks.
Test Samples

In addition to currency with known watermark designs, two sets of paper samples were examined with both electron radiography and low energy X-ray radiography. Examples of paper currency used as test samples with watermarks, included US dollars, Euros, and Chinese Yuans as shown in Figure 5. A second set of test samples with examples of historical papers with watermarks and mould patterns are presented in Figure 6.

![Figure 5. Examples of Paper Currency with Watermarks.](image)

![Figure 6. Examples of Historic Papers with Watermarks and Mould Patterns.](image)

PRELIMINARY RESULTS AND DISCUSSION

An example of an electron radiography film image obtained with a sample of historic paper is shown in Figure 7. The same experiment was conducted on paper currency with the resulting image shown as Figure 8. The image quality for both watermark and mould patterns is judged as very good, and the images of printing inks are completely absent. The scratches at the left bottom corner of Figure 7 (b) are artifacts due to handling during the chemical film development process. In terms of potential for implementation in a library, film radiography requires a dark room and chemical development of the film. After development, the film requires a camera or scanner to manually digitalize the final image. This process is both costly and time consuming.
FIGURE 7. Examples of Electron Radiography from Historical Paper Using Film.

(a) Paper on light box  (b) Electron Radiography Image

FIGURE 8. Example of Electron Radiography Using Film as Detector.

(a) Dollar bills on light box  (b) Electron Radiography Image
Examples of electron radiography images by CR imaging plates from US dollar and Euro bills are given in Figure 9. A high pass filter was applied to the digital raw images to enhance the contrast. The image of the watermark obtained is judged as very good with negligible interference from the anti-forgery printed inks.

(a) Paper on light box  (b) Electron Radiography Image  (c) Low Energy X-Ray Digital Radiography

A comparison between images obtained with the film based electron radiography and DDA-based low energy X-ray digital radiography are shown in Figure 10. It is seen that the low energy X-ray radiography generates similar or better image quality with higher contrast and signal to noise ratio employing a shorter exposure time to acquire the watermark images. It does not however always remove all the artifacts resulting from the printed letters as well as electron radiography, as is seen in Figure 12. An example of a CR IP image for the watermark image zone in the same sample paper with higher noise level is shown in Figure 11.


The images shown in figure 12 compare the results obtained with electron radiography and low energy X-ray radiography imaging of US dollar bills. The anti-forgery ink in dollar bills causes some interference for low energy
X-ray radiography in terms of watermark extraction. The images show heavy residual printed details due to the high-density materials used in the ink.

**SUMMARY**

This paper reports a demonstration of the feasibility of electron radiography (with film and CR) and low energy X-ray digital radiography (with CR and DR) for paper watermark extraction. Both methods provide similar quality watermark imaging. Electron radiography has a higher requirement for laboratory infrastructure and equipment (including need for a high energy X-ray tube), but it may provide higher image quality when special inks (such as those used as anti-forgery tools) are used in the printing media. Low energy X-ray digital radiography uses a low energy source with imaging plates or digital detectors. This technique can directly generate digital images using a relatively compact system, if sources, detectors and X-ray shields are optimized for this application. The examples provided show initial results for of watermark imaging using electron radiography and low energy X-ray digital radiography with different types of detectors, which were obtained. Future work will apply these techniques to a wider range of paper samples, and conduct quantitative comparisons. The ultimate objective of this work is to establish the basis for a compact radiography system designed to extract watermarks on-site, accurately, safely, and cost-effectively, for the paper science community.

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