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# Wavelet-based image restoration of compact X-ray microscope images

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**Abstract.** Compact X-ray microscopy employing optics, such as mulitlayer mirrors and zone plates, with limited collection angles and efficiencies will always be limited on photons for short exposure times. Thus, it is important to investigate methods for improving the signal-to-noise ratio in the images. We show on data taken with the Stockholm laser-plasma-based X-ray microscope at 3.37 nm that a wavelet-based denoising procedure has potential to reduce the exposure time a factor 2 without loss of image information.

## 1. INTRODUCTION

We have developed a compact X-ray microscope based on a laser-plasma source. Such a table-top microscope shows promise for the use in small-to-medium-scale application laboratory. However, the low photon flux of our source results in a limited signal-to-noise ratio for short exposure times and makes it important to restore images after the acquisition process to improve image quality.

The goal of this work is to improve the image quality of the images provided by the compact X-ray microscope built in our laboratory. Different image restoration methods have been designed and tested over years. Previous attempts for improving X-ray microscopy images are limited to a few articles [1].
In the present paper we evaluate the use of wavelet analysis, in particular wavelet denoising algorithms. Wavelet-based denoising has intrinsic advantages and has proven more effective than, e.g., classical Fourier methods.

## 2. PARAMETERS OF THE COMPACT X-RAY MICROSCOPE

Our compact full-field X-ray microscope ([2], [3]) is based on a 100 Hz, negligible-debris, high-brightness ethanol liquid-jet laser-plasma source providing $\lambda$=3.37 nm radiation from carbon-ion emission with narrow line width. The source is combined with a spherical $W/B_4C$ normal-incidence multilayer mirror, which operates as condenser. The high-resolution imaging is performed with a 7.3% efficient nickel zone plate with an outermost zone width of 40nm. Detection is performed with a back-illuminated CCD camera with a pixel size of 24 x 24$\mu m^2$.

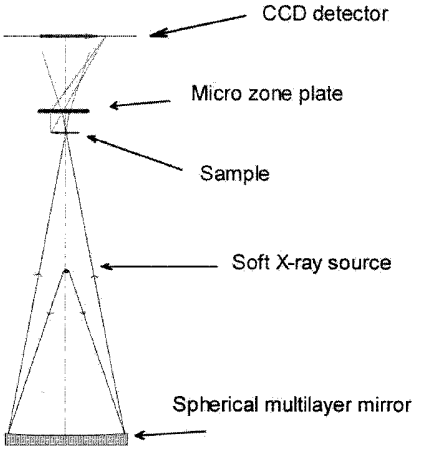


**Figure 1**: Principle setup of the compact X-ray microscope

## 3. WAVELET DENOISING

The wavelet denoising technique was applied to the images in order to improve their signal-to-noise ratio so as to make it possible to obtain the same quality images compared to untreated images within a much shorter time of exposure. This technique allows one to achieve a space-adaptive smoothing at low computational price, which makes it well-suited for applications to microscopy (see [4] for a general reference on wavelets in image processing).

The procedure that we used is the one described in [5], which has proven particularly effective in applications to confocal and two-photon microscopy. In short, a non-decimated, discrete wavelet transform (DWT) is applied to an original, noisy image. This produces a series of filtered images corresponding to different scales of resolution, from which the original image can be recovered by applying an inverse DWT. A thresholding is applied to the finest scales of the DWT, by setting to zero all wavelet coefficients of magnitude below a prescribed level. Applying the inverse DWT to the thresholded DWT then produces a denoised image. A different threshold level must be used for each scale, which can be estimated by a mean-square analysis of the data. In practice, however, manual tuning of the thresholds around the values found by the mean-square estimation is necessary to obtain optimal results. For more details, the reader is referred to [5].

## 4. RESTORATION OF IMAGES

The purpose of this experiment was to observe the results of the restoration and to optimize the restoration parameters. We used a Siemensstar as a test object. The star pattern, manufactured in nickel, has a finest structure width in its innermost part of about 70 nm. The imaging was performed with a micro zone plate with an outermost zone width of 40 nm.

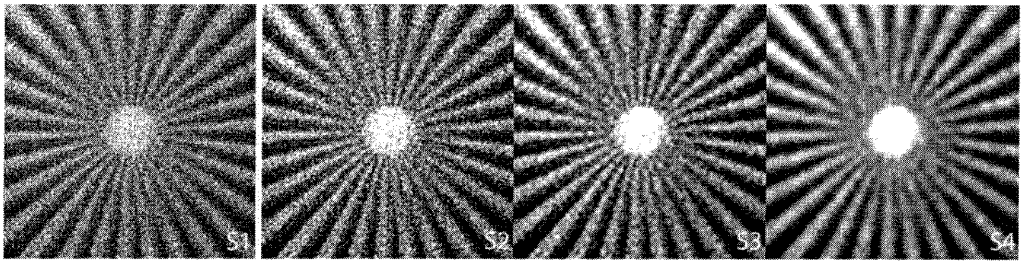


**Figure 2**: Image of a Siemensstar
S1: initial image, exposure time 7s, S2 – S4: restored images for thresholds at different scale levels.
The image size is 8 μm x 8 μm at 1000 times magnification.

Figure 2 shows on the left the initial image of the star pattern at 1000 times magnification, obtained with 7s of time exposure. Figures S2, S3 and S4 show the restored image for different scale levels. For the images S2 and S3, we can observe a gain in the signal-to-noise ratio compared to the initial image S1. The smaller structures are more clearly visible than in the original image, whereas in the image on the right (S4) one can observe a loss of information in the smaller structure.

The investigation resulted in that for the most applications it is sufficient to use the mean-square thresholds computed for the different scales, and to affect these thresholds with an equal weight in order to optimize the restoration. With this procedure we could limit ourselves to the first two scale levels in the wavelet transform. Thresholding of the third and coarser scales caused a loss of information in the smaller structures near the resolution limit, as illustrated in Fig. 2 (S4). Therefore, depending on the structure size, we applied the thresholding on one or two scale levels.

## 5. CONCLUSIONS

The results of the restoration process indicate that we can enhance image quality significantly. A rough estimation shows that it is possible to lower the exposure times by more than a factor of 2 without loss of image quality and information. Shorter exposure times improve the operability of the compact X-ray microscope for applications. In addition it reduces the radiation dose and therefore radiation damages caused by the X-ray imaging on biological samples.

### Acknowledgments

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