RESTORATION AND INTERPRETATION OF IMAGES FROM THE YOHKOH SOFT X-RAY TELESCOPE

J. Shin and T. Sakurai

National Astronomical Observatory, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

ABSTRACT

Due to the finite width of the point spread function (PSF) of the *Yohkoh* Soft X-Ray Telescope (SXT) mirror, a certain amount of blurring effect is inevitable in the observed soft X-ray images. Thus it is necessary to subtract its effect from the observed images for both morphological and photometric purposes. Because of undersampling due to a large pixel size of the CCD camera of SXT, however, the application of general algorithms to image restoration has so far been unsatisfactory for the SXT images. Therefore, we have developed a new method for increasing the sampling density of *Yohkoh* SXT images under the condition of photon number conservation in each pixel. The correction for the undersampling effect was also necessary to obtain a good estimate of the PSF from the ground experimental data. Based on this best-fit PSF, we apply the maximum entropy method algorithm to the observed SXT images. The restored images succeed in showing fine details in coronal loops, but there still remains the problem of insufficient noise suppression.

INTRODUCTION

Since the launch of *Yohkoh* in 1991, the Soft X-Ray Telescope (SXT) has provided images of the solar corona with unprecedented resolution and time cadence. The SXT coronal images are used not only for morphological studies, but also for quantitative studies of spatial distribution and temporal variation of physical parameters (temperature, density, etc.) of various structures and events in the solar corona. In order to derive physical parameters from SXT images, one has to go through a series of calibration procedures, namely dark frame subtraction, flat fielding, and correction for scattering from surrounding brighter areas. However, even after these procedures, SXT images still do not present completely sharp structures of the solar corona because of the finite resolving power of the telescope. What is recorded by the CCD during an observation is the result of convolution of the real X-ray intensity distribution of the solar corona and the blurring pattern by the telescope mirror. The blurring pattern on the grazing incidence mirror of the SXT, the point spread function (PSF), can be described by the Moffat function representing the core portion and a power-law distribution for the scattering wing (Martens *et al.*, 1995; Hara *et al.*, 1994). Although the level of scattering of the SXT mirror is much reduced compared to the *Skylab S-054* telescope, there is no doubt that the convolution blurs the original coronal structures.

A good deconvolution procedure will subtract the blurring effect and, in addition, suppress the noise inherent in the observed image. For the SXT images, however, such deconvolution procedures are not usually applied. Although there have been some trials of the deconvolution for the SXT images, it seems the results have not been positively accepted by the *Yohkoh* scientists for some reasons. It is certainly true that, because the PSF of the SXT mirror has a very sharp core and a widely spread wing, the overall feature of the observed images would be very close to the original structures, morphologically. One may therefore think that it is not necessary to correct for the blurring effect or the noise in the observed images. However, this is indeed a dangerous idea, especially when accurate photometry of coronal features is aimed at. In the following we will argue that the restoration of the observed *Yohkoh* SXT images should be performed for obtaining correct information on the solar corona, and a method for such image restoration will be presented.

DECONVOLUTION AND UNDERSAMPLING EFFECT

The goal of the image restoration is to recover the original features from degraded observations. Image restoration techniques are oriented towards modeling the image degradation (blur and noise), and applying an inverse procedure to obtain an approximation of the original features. Mathematically, the restoration of an image is defined by an inversion of the image equation (*i.e.*, a deconvolution to remove the blur), together with a statistical regularization of the noise in the observed image. Numerous algorithms for finding the best solution of the true image have been developed so far. However, as has been shown in the numerical simulation by Shin (1998), the deconvolution of the SXT images is hindered by the undersampling effect included in both the observed images and the PSF. It was known from the ground experiments (Tsuneta *et al.*, 1991; Martens *et al.*, 1995) that the full width at half maximum (FWHM) of the PSF of the *Yohkoh* SXT is only as large as one pixel size (2.45 arcsec), which means the observed SXT images are not adequately sampled. Aside from the loss of spatial resolution, it is clear from simulations (Shin 1998) that it produces a mathematical artifact during the deconvolution, and this kind of artifact acts as a mechanism for producing negative structures in the deconvolved images. Therefore, without increasing the sampling density of the observed images it would be impossible to restore them in a reasonable way. However, a simple adoption of a smoothing kernel in increasing the sampling density would be dangerous because it changes the whole intensity distribution of the observed images in an uncontrolled fashion. In order to perform photometric studies using the SXT images, we believe that the energy distribution (photon counts in the pixels) of an image should not be distorted by any kind of smoothing processes. We also suggest that the restored image should not contain structures with spatial scales much smaller than the CCD pixel size.

In order to remove the undersampling effect from the observed images under the condition of energy conservation in each pixel, a method of variance optimization inside of and between pixels has been developed (Shin, 1998). The method generates a smooth distribution of intensity by conserving photon counts in the pixels. It has been tested on several sample two-dimensional images, and proved to be successful in increasing the sampling density of the undersampled images. Figure 1 shows a comparison of an observed image (left panel) with the images whose sampling density is increased (middle panel). The sampling density is increased by dividing each pixel into 4×4 ($= 16$) sub-pixels. Photon number conservation in each pixel is satisfied among these images. We found that sub-pixel division beyond 4×4 does not change the result much in the following deconvolution procedure.

For performimg the deconvolution of the images, the sampling density of the PSF data must be increased at the same time. The experimentally determined shape of the PSF suffers heavily from the undersampling effect, as we may expect from its sharply peaked shape. The result (Sakurai and Shin, 1998) shows that the PSF has a shape slightly sharper than that given by Martens *et al.* (1995), and begins to be smoothly connected to the scattering wing at the distance of about 15 arcsec from the center.

RESTORATION OF YOHKOH SXT IMAGES

In this study, we have adopted a slightly modified form of the maximum entropy method (Agmon *et al.*, 1979; Hollis *et al.*, 1992) for the restoration of the observed SXT images. This provides an alternative to the conventional procedure which requires the numerical solution of a set of implicit nonlinear equations for the Lagrange multipliers. Here the solution is determined by seeking a minimum of a potential function which is concave for any trial set of Lagrange multipliers. The right-most image of Figure 1 shows the result of deconvolution starting from the densely-resampled SXT image which is shown in the middle panel. Fine details of a coronal loop structure are clearly seen. Due to the deconvolution, the X-ray intensity at the brightest peak is increased by about 20%. The largest difference between the raw and the deconvolved X-ray intensities is found at locations with large intensity gradient.

We noticed that the noise components are not fully suppressed in the restoration procedure. This is because, although the sampling density of the images is increased, still the size of the noise components and the FWHM of the PSF is of the same order as the original pixel size. In this situation, it is difficult to expect a successful statistical consideration of the noise components from any of the usual restoration algorithms. For this reason, we introduced a shift-variant filter to the restoration algorithm. The size of the filter for a certain location is determined in such a way that the summed intensity over the area is equivalent to 600 DN (data number, which is roughly an X-ray photon count). For

this photon count, the temperature obtained from the restored image will have an error range of about 10% (Yoshida *et al.*, 1996).

The level of the scattering wing is accurately estimated for the thin aluminium filter only. For other filters there exist uncertainties in the level of the scattering wing, and therefore, in the overall shape of the PSF through the normalization of the PSF. Figure 2 shows the results of the restoration for images of a flare observed on February 21, 1992 (Tsuneta *et al.*, 1992). The images were taken through the thick aluminium filter and the berylium filter, whose passbands are at higher energies than that of the thin aluminium filter. Although the noise components are suppressed in the dark areas to some extent, it seems the blurred components still remain in the restored images. This must be related to the fact that the scattering level considered in our study might be underestimated. It should be noticed that the physical quantities obtained from the dark regions on the restored image are very sensitive to the consideration of the level of the scattering of the PSF. Therefore, for a precise estimation of the physical parameters of the solar corona, especially for dark regions around bright structures, it is necessary to consider seriously the level of the scattering intensity. This last point will be elaborated upon in our future papers.

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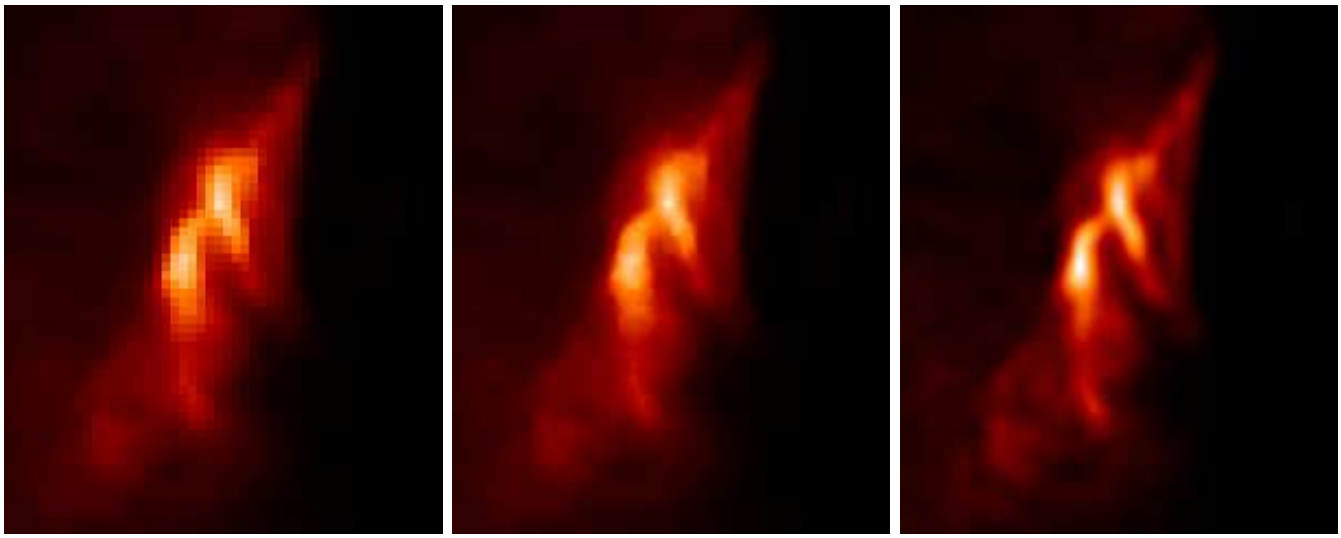

Fig. 1. An example of raw SXT image (left) and the image whose sampling density is increased by 16 times using the variance optimization method (middle). The right-most image is the result of maximum entropy restoration of the image in the middle panel.

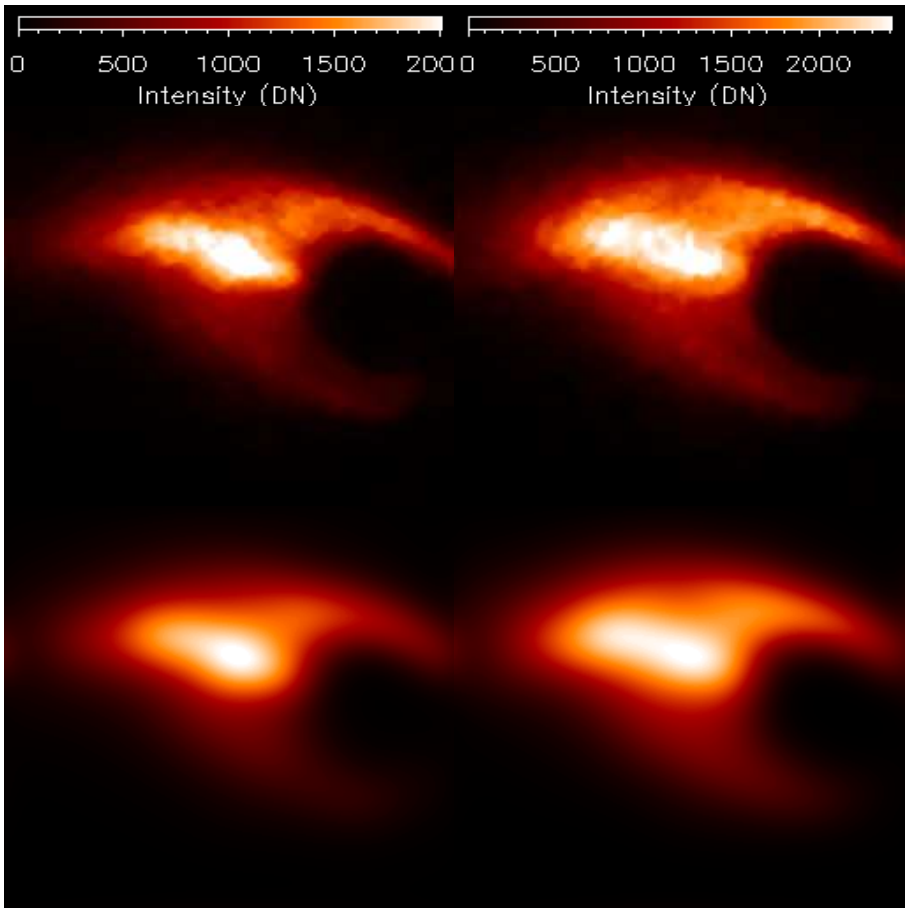

Fig. 2. Comparison of the observed (top) and the restored SXT images (bottom) of a flare observed on February 21, 1992. The images in the left are for the thick aluminium filter and those in the right are for the beryllium filter.