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Deconvolution of Substepped 1-D and 2-D HST Data

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Abstract. Substepping is a technique in which data are acquired in steps smaller than the normal pixel size, such that resolution after restoration will be comparable to the subpixel size. Substepped data have been acquired by first generation HST instruments in both one-dimensional (spectroscopic) and two-dimensional (imaging) modes. In this presentation, we first introduce the principle of the substepping technique and then demonstrate numerical examples of MEM (Maximum Entropy Method) deconvolution of an FOS ACQ image of a star as well as of an FOS stellar spectrum.

1. Introduction

Substepping is a technique in which data are acquired in steps smaller than the spatial or spectral resolution element defined by an instrument's hardware. It may be done in two dimensions for imaging or in one dimension for spectroscopy. Substepped data may be restored by direct combination methods or deconvolution. The ultimate resolution may be comparable to the subpixel size (Wu & Caldwell 1997).

Substepping may be useful when the instrumental resolution is significantly worse than the inherent resolution of the optics of the telescope. It has been successfully applied to WFPC2 imaging (dithering). In data acquisition, this is achieved by small HST slews, of order 10 mas. For restoration methods, see Hook & Fruchter (1997) and Adorf (1995).

Substepped FOS imaging and spectroscopic data have also been taken, but very little attention has been paid to reconstructing these data optimally.

For FOS ACQ imaging we present a comparison of two reconstruction techniques, MEM deconvolution and the IRAF/STSDAS task `tarestore`. For FOS spectroscopy we present, apparently for the first time, MEM deconvolution of a substepped spectrum.

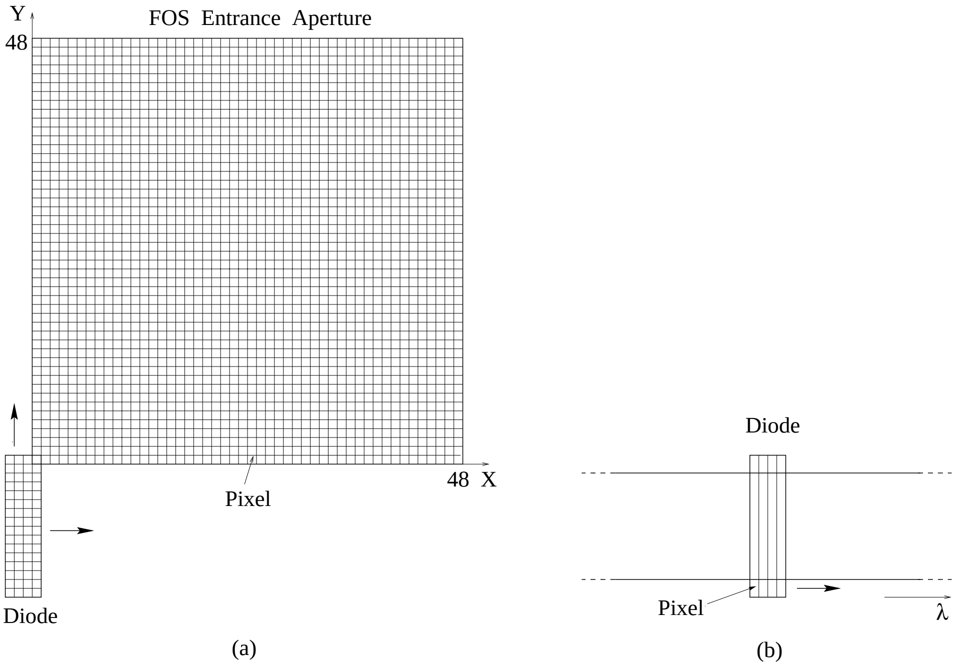
It should be emphasized that deconvolution here is used to eliminate the "moving-sum" effect in substepping to improve resolution, but does not address the problem of the effect of the HST PSF (point spread function, in imaging) or LSF (line spread function, in spectroscopy) on resolution.

2. Application of Substepping to FOS ACQ Imaging

2.1. Data Acquisition

As shown *schematically* in Fig. 1a, the FOS entrance aperture is divided into 48 × 48 "pixels". (They would have been named "subpixels" according to standard substepping terminology.) The diode footprint has a size of 4 × 16 "pixels". (The diode footprint would have been named "pixel" in standard terminology.) Starting from position $(1, 1)$, the diode (used to collect photoelectrons) moves in a raster scan. The step in each direction (pixel size) is equal to one quarter of the diode width, or equivalently, one sixteenth of the diode height. (In reality, the substepping is achieved electronically, i.e., photoelectrons are

Figure 1. Schematic substepping with FOS. (a) ACQ imaging. (b) Spectroscopy.



deflected magnetically and the diodes are fixed in position.) Therefore, in each step the photoelectrons collected by a diode are the sum of the photoelectrons in 64 (= 4 × 16) pixels.

2.2. Task tarestore for Reconstruction

The task `tarestore` in IRAF/STSDAS was written based on the moving-sum model of data acquisition (Oegerle 1989). As shown in Fig. 1a, in each of the diode's positions, (i, j), the number of photoelectrons collected by the diode is

$$D_{i,j} = \sum_{k=p}^{q} \sum_{l=r}^{s} P_{k,l}$$

where $P_{k,l}$ is the number of photoelectrons in pixel (k, l); $1 \leq i \leq 48 + 4 - 1$, $1 \leq j \leq 48 + 16 - 1$; $p = \max(1, i - 4 + 1)$, $q = \min(48, i)$, $r = \max(1, j - 16 + 1)$, $s = \min(48, j)$.

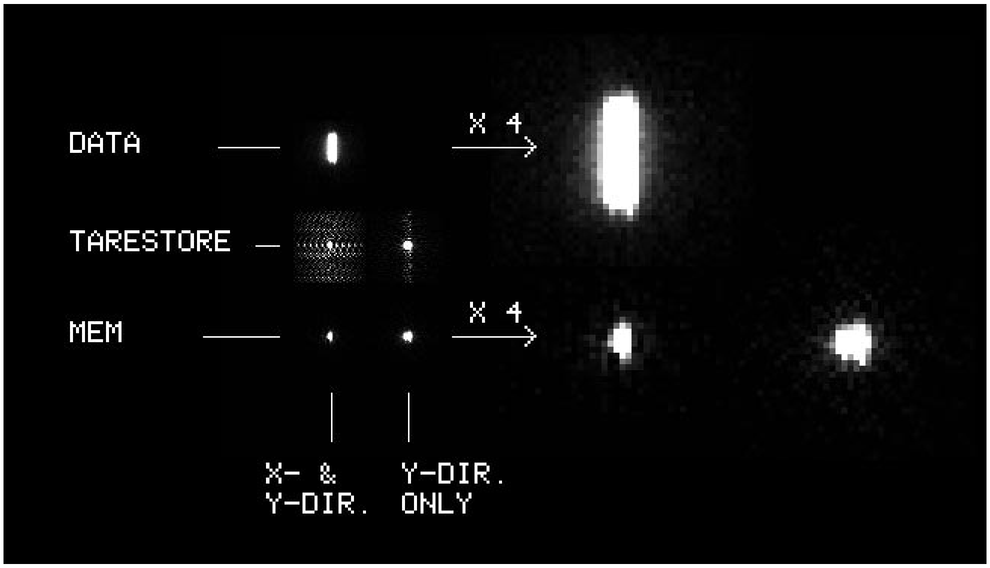
The above linear equations can be solved by the generalized inversion of a matrix to reconstruct the photoelectron distribution $P_{k,l}$ (an image).

As a direct inversion method, the above algorithm cannot handle the high frequency components in the signal correctly, and is extremely sensitive to noise. Consequently, reconstruction is usually done only in the Y-direction. The moving-sum effect in the X-direction is not removed, i.e., the summation for k from p to q is not inverted. Otherwise the reconstructed image would have excessively high level sidelobes (rings) and noise. As a result, it would be nearly impossible to extract useful information from the reconstructed image.

2.3. Convolution Model and Deconvolution

If the area outside the aperture is also divided into pixels (without photoelectrons), then the limits p, q, r, s in the above moving-sum model can be set arbitrarily, and a crosscorrelation model and hence a convolution model may be applied. Consequently, deconvolution can be

Figure 2. FOS ACQ images of the star Wolf 359. `X 4` means magnified by a factor of 4; `X- & Y-DIR.` means reconstructed in both X- and Y-directions; and `Y-DIR. ONLY` means reconstructed only in the Y-direction.



used to reconstruct the image $P_{k,l}$. In principle, any deconvolution program can be used for this purpose. In particular, the tasks `mem` and `lucy` in IRAF/STSDAS are most convenient, and give very good results.

2.4. Numerical Example

Figure 2 shows FOS ACQ images of the star Wolf 359. The image before reconstruction (`DATA` in the top row) is essentially the shape of the diode.

The images reconstructed by the task `tarestore` (especially the one reconstructed in both X- and Y-directions) in the middle row have high resolution, and strong sidelobes (rings) and high level noise. In practice, only the image reconstructed in the Y-direction only can be used for analysis.

In contrast, the images reconstructed by `mem` in the bottom row have high resolution and insignificant sidelobes and noise. The price paid is the computational complexity.

3. Application to FOS Spectroscopy

3.1. Data Acquisition

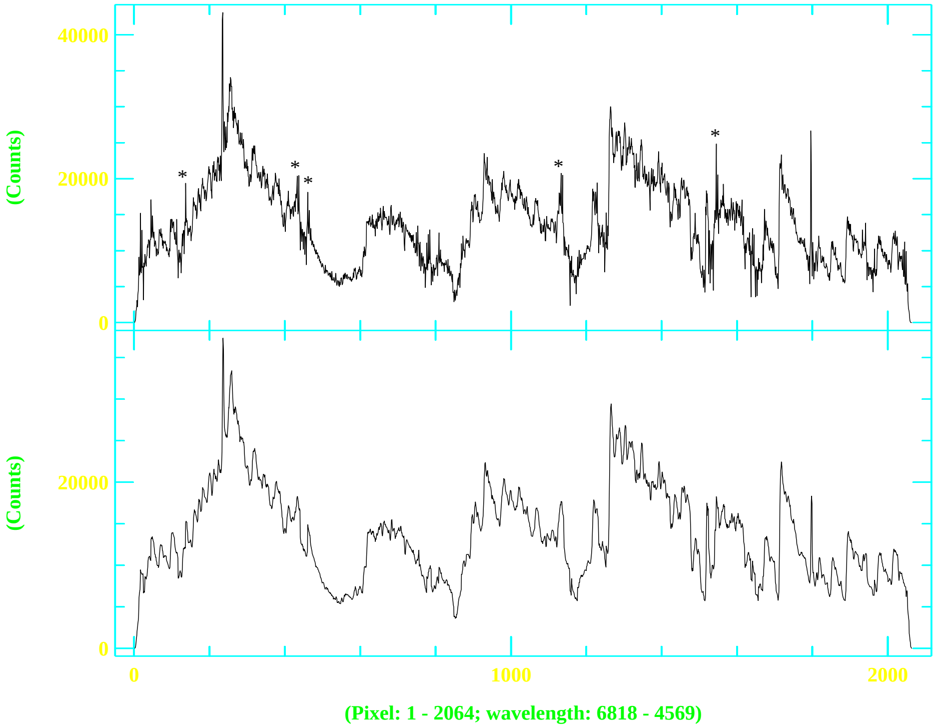
Because the diode's width along the dispersion (λ) direction in spectral data acquisition is too large, the substepping technique is used to improve spectral resolution (Fig. 1b). The substepping factor is 4, i.e., the diode moves in steps of a quarter of the diode width.

3.2. Convolution Model

The output data from the diode is a moving-sum of 4 pixel values in the λ direction. Therefore, the spectral data acquisition can be modelled as convolution, and, potentially, the resolution in spectra can be improved by deconvolution.

Only the task `mem` in IRAF/STSDAS is available for this purpose. The task `tarestore` was written specifically for reconstructing FOS ACQ images, and `lucy` contains bugs in the 1-D case.

Figure 3. FOS spectra. Lower: data. Upper: `mem`.



3.3. Numerical Example

Deconvolution by `mem` was attempted on a spectrum of Proxima Centauri (G570H, $\lambda\lambda$ 4569–6818). As shown in Figure 3, the resolution seems to be improved. There is more fine structure (indicated by asterisks) in the `mem` spectrum.

Before applying this deconvolution technique, the following questions must be answered by computer simulation and real data tests: Are the extra peaks in the `mem` spectrum real? Is it worth doing deconvolution at all for a signal whose bandwidth is limited by the optical system?

References

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