

& Feel based on OSF/Motif depending on the user feedback.

Significant contributions were added in the application area as well. The IRSPEC reduction was revised by T. Oliva, while an image restoration and co-addition application, based on ideas of L. Lucy, was added by R. Hook (ST-ECF). A Time Series Analysis context, which includes analysis of non-equally spaced data, was made by A. Schwarzenberg-Czerny. Finally, a photometry scheduling programme was introduced by A.T. Young as the first application in a new context for calibrations of point-

source photometry.

There are now more than 160 registered MIDAS sites, of which approximately 100 are in the ESO member States, 30 in other European countries and 16 in North America. Since many of these sites have several different computer systems, this represents a significantly larger number of installations. Our current statistics (not fully complete) show that 70% of the systems run UNIX, while the remainder have VAX/VMS. Of the UNIX systems, the distribution between different vendors is 42%, 21%, 15% and 7% for SUN/SPARC,

DEC, HP/Apollo and IBM, respectively. The MIDAS site data-base as well as problem reports are available through the starcat account on the host dbhost.hq.eso.org.

A number of MIDAS information services are provided through Internet or e-mail. A bulletin board can be accessed by login on the esobb account on bbhost.hq.eso.org. Documentation and patches can be obtained through anonymous ftp from ftphost.hq.eso.org. General questions and problems can be mailed to the MIDAS hot-line account midas at eso.org.

## FFT Removal of Pattern Noise in CCD Images

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### 1. Introduction

The second-generation CCD detectors at ESO have very greatly reduced readout noise. This noise reduction allows ESO astronomers to extend their observations to fainter sources. Unfortunately, with the lower detector background, electronic interference noise now often becomes the limiting background noise source. It is thought that this noise is mostly generated by the switching power supplies that are used in the CCD controllers (Roland Reiss, private communication). These are to be replaced in the near future by less noisy power supplies, but in the meantime it is useful to search for ways to remove the interference from existing frames as well as to develop tools to cope with possible future problems.

After experimenting with the MIDAS Fast Fourier Transform (FFT) packages,

a simple way has been found to obtain a considerable reduction in the pattern noise seen in the ESO CCD frames. Because this method may be useful to others, it is described here in some de-

tail. Briefly, the technique is a crude approximation of Wiener, or optimal, FFT filtering. See Brault and White (1971) or Press et al. (1988) for descriptions of Wiener filtering using FFT.

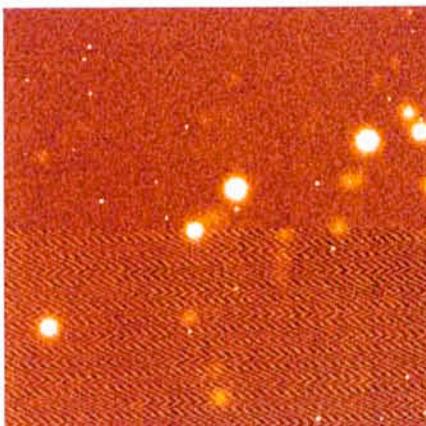


Figure 1: A comparison of an unfiltered frame (lower half of the image) with a FFT filtered image (upper half).

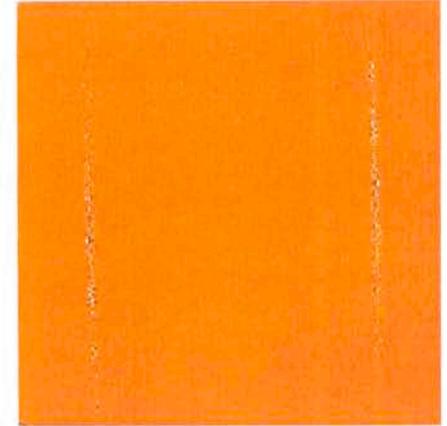
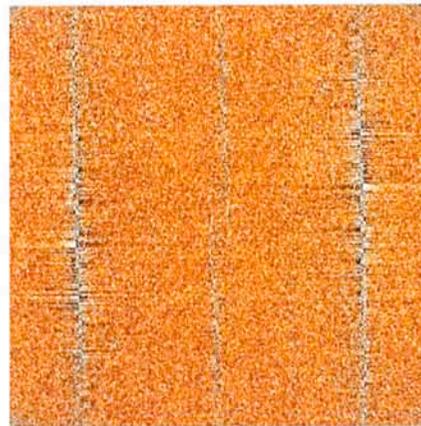
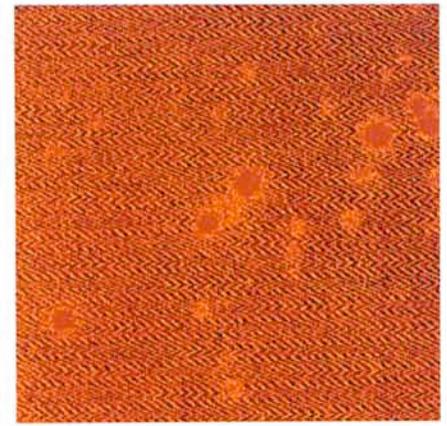


Figure 2: Frames produced during the filtering process. a: The real FFT image of the raw input frame. b: The raw input frame with the stars replaced by the median value of the background. c: The real FFT image of the frame shown in panel b. d: The real FFT image after setting all low amplitude pixels (both positive and negative) equal to zero.

## 2. FFT Cleaning of CCD Frames

Figure 1 shows a split-frame image of SN 1987 A taken with SUSI in September 1991 using a very narrow-band redshifted HeII  $\lambda 4686$  filter. The lower part of Figure 1 shows the received data frame, which is contaminated with electronic interference. The upper part of the figure shows a matching section of the same frame after using the cleaning procedure described here. The beginning steps of the procedure are shown in Figure 2. Frame 2a shows the real FFT image of the frame. For illustration purposes I am only showing the real image in the transform domain; the imaginary image is similar in appearance. The pattern in Figure 2a is dominated by the transform of the science data in the frame. The first step in separating the interference from the data and background noise is to remove as much as possible of the science signal from

the data frame. First, any low frequency irregularities of the frame are removed. Then, using the MIDAS command STATISTICS/IMAGE, the median value of the background is determined and set to some convenient value. By using the MIDAS command REPLACE/IMAGE, all pixel values above the highest ones found in the noise level are replaced by the background level. The result of this operation on the example given here is shown in Figure 2b. This modified frame is then transformed using FFT/IMAGE. The real part of the clipped image transform is shown in Figure 2c. Note that the background from the science signal, which, for our present purposes, behaves as a noise source, has now been greatly reduced. REPLACE IMAGE is used again to set all low amplitude components of Figure 2c and its imaginary counterpart to zero. The result of this operation is shown in Figure 2d.

This replacement procedure is similar

to the application of a Wiener filter to the transform except that replacement by zero creates a filter function that is a truncation rather than a gradual roll-off. This is not too serious as we will iterate the resulting frame once. Because MIDAS does not have a simple procedure for constructing and applying FFT filters and because the FFT procedures are so fast, it takes less time to run through the procedures twice than it does to construct an optimal filter. In any case, the results of the interactive procedure described here, seem to be nearly as good as those that could be obtained by a more careful filtering procedure.

The filtered images in the transform domain are transformed back to the measurement domain by using the MIDAS command FFT/INVERSE. This inverse transform results in real and imaginary frames which must be combined by taking the square root of the sum of the squares (remember that the square of an imaginary number is negative). Figure 3a shows the output frame. Note that both the science signal and the shot-noise in the input frame have now been greatly reduced, although faint evidence of the input signal at the positions of the bright stars can be seen. Subtracting the output frame from the input frame gives a substantial reduction of the pattern noise (see Fig. 3b). However, because a rather strong cut was used to filter the images in the transform domain some residual patterned structure remains in the background. For instance, note that a structured band still remains at the top of the frame. A strong cut of the frames in the transform domain was needed to suppress the science signal in the output image. But now that we have a first estimate of the pattern noise at the star positions in the input frame (Fig. 3b), we can replace those star images with this pattern. A mask for this can be produced from the star field by using the MIDAS commands REPLACE/IMAGE, FILTER/SMOOTH and then REPLACE/IMAGE again. Try to have the mask extend beyond the immediate neighbourhood of the star positions. Then by using REPLACE/IMAGE and INSERT/IMAGE the stars in the input image are replaced by the pattern image. This operation further reduces the signal from the science data and allows us to lower the cut values for the transform domain images. Figure 3c shows a second iteration of the FFT input frame and Figure 3d shows a comparison of the final output with the intermediate output.

Finally, Figure 4 shows the background statistics obtained for a patch of sky in the frames produced during the different steps of the pattern removal

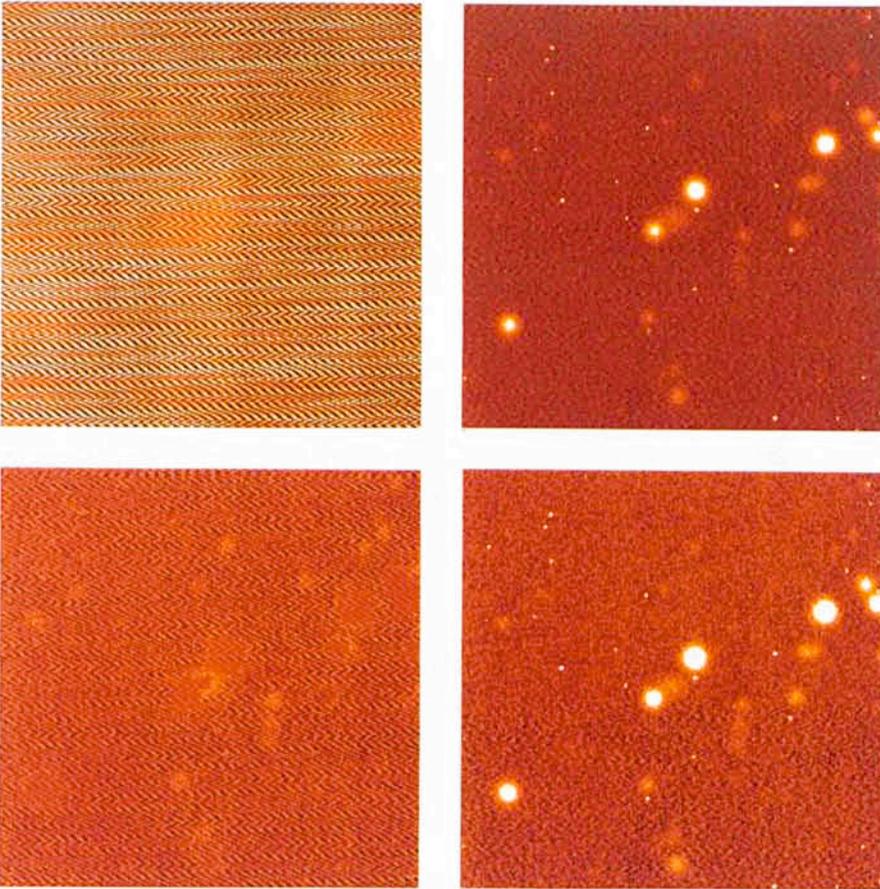


Figure 3: Frames produced during the filtering process (continued). a: The inverse FFT of the filtered FFT frames (Fig. 2d). The interference pattern is now clearly seen with only a faint trace of the star images. b: The result of subtracting the pattern noise (panel a) from the input image. Note the imperfect cancellation of the pattern noise. c: The raw input frame with the star images replaced by an appropriate section from the FFT image of the pattern noise (panel a). Here the cosmic rays have also been replaced with the median background value. d: After the FFT of panel c was clipped, the new image of the inverse transform was subtracted from the raw input image. The resulting output image (upper half of the frame) is compared with the intermediate output from the first pass (panel b, lower half).

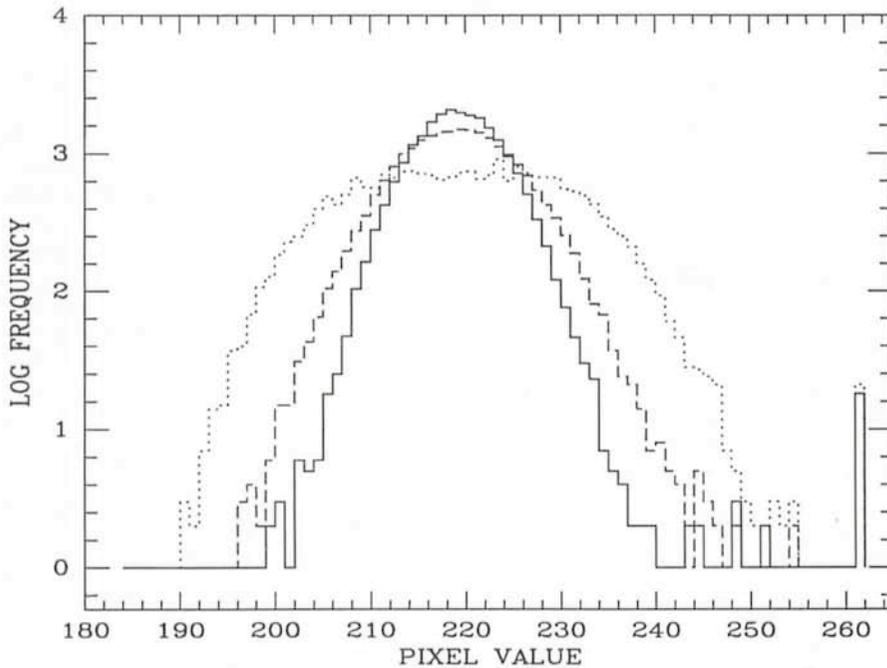


Figure 4: The background statistics of the images. Dotted line: the input image; dashed line: an intermediate output; solid line: the final output. See the text.

process. The distribution of pixel values for the input frame (dotted line) shows the wide, flat peak caused by the interference pattern noise. This is greatly

reduced after the first pass through the FFT filter. At this stage the distribution of pixel values in the log-linear plot looks like an inverted parabola, suggesting

that the distribution of values is nearly Gaussian. After the second iteration the width of the distribution has been further reduced, allowing improved detection of threshold stars. The use of a proper Wiener filter would result in optimal noise reduction but would require a MIDAS programme that could adjust the value of low amplitude signals in the transform domain by factors that depend on the signal amplitude. The cleaning procedure described here is logically very similar to the procedure by Adorf and Catchpole (1992) for creating a filter by isolating a domain in Fourier power space. The sharp edges of his domains are equivalent to a box filter, as is used here, rather than the optimal Wiener filter.

I am indebted to L. Lucy for pointing out the references to Wiener filtering.

#### References

- [1] Brault, J.W. and White, O.R. 1971, *A & A*, **13**, 169–189.
- [2] Press, W.H., Flannery, B.P., Teukolsky, S.A. and Vetterling, W.T. 1988, *Numerical Recipes in C* (Cambridge University Press, Cambridge) p. 434 ff.
- [3] Adorf, H.M. and Catchpole, R. 1992, in *ST-ECF Newsletter*, February, 16–17.

## Adaptive Optics on the 3.6-m Telescope: Latest News!

After several strenuous months of assembly and testing, the Come-On-Plus Adaptive Optics system has finally come to life in the "Laboratoire d'Interférométrie Infrarouge et d'Optique Turbulente (LYOT)" of the Observatoire de Meudon, under ONERA's supervision. Thanks to LASERDOT, who designed the control computer and the deformable mirror, the closed-loop 40-Hz bandwidth performance (at 0 dB) has been achieved. The LEP (Laboratoire d'Electronique Philips) delivered the EBCCD (see *The Messenger* No. 67), a low-flux wavefront sensor detector, which is a quantum noise limited detector with a switchable frame frequency from 25 to 400 Hz. The 52-actuator deformable mirror has been tested with successful results. The actuators, made of a very hard piezoelectric material, show no hysteresis or heat dissipation at all, and the mechanical bandwidth is more than 10 KHz (far more than required for an atmospheric turbulence correction). The surface quality is also very good: by means of a self-correc-



tion, the mirror can lower its own wavefront residual error to less than 20 nm rms. The whole system is now ready to

be tested on the sky, under real conditions in December 1992.

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