FIXED PATTERN NOISE REVISITED

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ABSTRACT: Cross-correlation of high dispersion images frequently produces a sharp peak with approximatly a 1 pixel velocity width. The spike occurs between images taken years apart, and at the same velocity over a large area of the camera. It also occurs in the background of a pair of spectra. A characteristic camera pattern which persists for years and allows images to be aligned to the pixel fits the definition of "fixed pattern noise". The exact reproduction of the pattern over years suggests that improved flat-fielding may be possible.

I. Introduction

A number of studies have shown that in addition to the random component of noise in IUE spectra, there is a noise component which is not removed by adding together many spectra. Specifically, Clarke (1981) showed that when 14 SWP low dispersion images were added together, the noise decreased in proportion to $1/\sqrt{N}$, where N is the number of images, up to about N = 4. As more images were added, the noise fell off very slowly, indicating a non-random noise component, called the "fixed pattern noise". A summary of the studies of this fixed pattern noise is given by Grady and Imhoff (1985). In particular, three recent studies have investigated its characteristics carefully, together with ways to remove it. Adelman and Leckrone (1985) coadd images deliberately taken at different locations in the aperture. They conclude that about 40% of the noise is random, and about 60 % is fixed pattern noise. Joseph (1984) and Welty, York, and Hobbs (1986) discuss flat-fielding the image before adding. All studies report an increased signal to noise using the noise supression techniques.

Although the occurance of fixed pattern noise has been established, and some of its time and amplitude characteristics are known, its cause has never been definitively identified. Working on a completely different problem, the measurement of velocities on high dispersion spectra, we have been plagued with a different problem, which we believe is related to fixed pattern noise.

II. Observations

A number of IUE high dispersion long wavelength spectra of Cepheids with binary companions have been measured in order to determine the velocity difference between the companion and the Cepheid (e.g. Evans and Bolton, 1986). The velocities were measured by cross-correlating the Cepheid spectrum with the spectrum of a standard star using the RDAF program CRSCOR. In the course of the measuring, a sharp peak was often seen in the correlation function at a surprising velocity. Figure 1 shows an example of such a peak in 3 orders of the cross-correlation of LWR 9149 (the Cepheid Eta Aql) and LWR 12715 (Alpha Per F5Ib). The cross correlation functions have been arbitrarily offset. The strongest peak is normalized to 1.0. The ends of the orders are not used because of excessive noise. The main velocity signal between the Cepheid and the standard star is at 15 km/sec, as is shown much more clearly by the longer wavelength orders. We hasten to point out that the main peak in the cross-correlation function is much less noisy and better defined in the longer wavelength region, where both the late type spectra are much stronger. This is part of the reason for the surprise at the sharp, strong, consistent velocity peak at 45 km/sec. Although Eta Aql has been shown by IUE low dispersion spectra to have a binary companion, three arguments suggest that the sharp peak is not produced by the companion. First, the companion would have a very improbable velocity. Second, an extra peak is seen in cross-correlations of spectra of single stars such as Alpha Per and Alpha Lyr. Finally, the width of the peak is much narrower than features which are really stellar, as can be seen in Figure 1 top (also in Figures 2 and 3).

The sharp peak, however, does recur at the same velocity for many sucessive orders. For the pair of spectra used in Figure 1 it is prominent from 2635 to 2280 Å. Since the cross-correlation function is normalized to the strongest signal, the disappearance of the sharp peak in some regions of the camera is probably due to a proportionaly stronger stellar signal.

Conclusive proof that the sharp peak is instrumental, and not stellar, is provided by cross-correlation of the backgrounds of an order for spectra in which the sharp peak is seen. Figure 2. shows the cross correlation between LWR 12715 (Alpha Per) and LWR 7008 (Alpha Lyr). A sharp peak occurs in the background cross-correlation at the same velocity as it occurs in the stellar correlation.

In the process of cross-correlating about 20 spectra of different stars, we have found a number of characteristics of the sharp peak. They will be described in the remainder of this section.

The sharp peaks have been found only in the cross-correlations of spectra from the same camera and the same aperture. So far none have been found in LWP versus LWR correlations, nor in large aperture (LGAP) versus small aperture (SMAP) spectra. Figure 3 is an example of a spike present in LWP--LWP and LWR--LWR correlations which is removed in LWP--LWR correlations.

The spike appears in cross-correlations of spectra taken years apart, e.g. LWR 7008 (1980) versus LWR 12715 (1982). On the other hand, it does not appear in spectra taken very close together in time in different apertures. The sequence of spectra listed in Table 1 illustrates this. For the three images of Eta Aql listed on the left in Table 1, the spike which is present in the first two SMAP images, disappears 5 hours later in the LGAP spectrum, using either comparison image.

The spike occurs whether the standard star LWR 7008 is used with the original 1980 processing, or with recent reprocessing, indicating that it is not a simple artifact of the processing or the sampling interval. Smoothing one of the spectra with a Gaussian filter reduces the height of the sharp peak, but does not remove it altogether.

In order to investigate whether the sharp peak is the result of a periodic pattern in the spectrum, a power spectrum of the several orders of spectra showing the spike was created. (The flux samples were taken from SIPS processing: the wavelength steps vary by $\pm$ 6%.) They showed no sign of a strong periodic component. This is perhaps not surprising in view of the fact that the IUE extarction samples are taken on the diagonal of the camera read grid. It does, however, eliminate an easy method for removing the spike. It also underlines the surprise in frequently finding a sharp peak which repeats consistently for many orders.

The FWHM of the sharp peak is approximately 10 km/sec. This is very similar to the pixel spacing.

III. Discussion

Let us quickly review the situations for which the instrumental effect has been found. The spectra discussed here are point source, high dispersion spectra, processed with normal old and new SIPS processing, from all 3 cameras, and both apertures. The extraction technique means that the repeated noise pattern is found for fluxes obtained from a combination of several pixels. Welty, York, and Hobbs used unusual widened high dispersion spectra. Thus, the noise which they sucessfully decreased by dividing by a template comes from a larger area on the camera. That is, the persistant noise patterns which have been found from at least two different extractions involving a combination of several pixels.

The number of spectra investigated here (about 20) make it impossible to estimate accurately how often a spike appears in a same camera, same aperature correlation with a given standard image. It occurs at least very frequently. Since spectra fall on different areas of the camera for different camera temperatures, it is to be expected that the spectral alignment will be found between many but not necessarily all spectra if the pattern depends on which pixels are sampled. Rough checks on the spectrum location for typical temperature ranges show that shifts of 1 pixel perpendicular to the dispersion (point source point spread function 3 pixels) are common. No effort has been made to investigate the occurance of a spike as a function of the difference in camera temperature between the two exposures. Different placement of the target in the aperture could also sample different camera areas.

Note that on an echelle spectrum, a shift in the location of the spectrum on the camera along the dispersion because, for instance, of a change in camera temperature results in an apparent velocity shift in the spectrum which is the same for all orders. The range of velocity shifts in the figures (up to about 50 km/sec between two spectra) suggest shifts of up to approximately 3 pixels between spectra which can still register correlated noise patterns.

The spikes in the cross-correlation functions indicate that it is frequently possible to align spectra taken years apart to pixel accuracy, order by order over a large area on the camera. It seems unlikely that this accuracy and consistency would be produced by an electronic artifact, such as part of the read-out process. The precision with which the pattern can be located makes a noise pattern imbedded in the camera a likely suspect. If this is the case, then, of course, the ITF flatfielding cannot be complete, or the pattern would be removed at that stage. If there is an unchanging noise pattern produced by the camera, there are two ways in which it could remain uncorrected by the ITF (Imhoff, 1897). First, the ITF has random errors which will be applied to every processed spectrum. This source can be checked by reprocessing one image of a pair which shows the instrumental signal with the new ITF. The cross-correlation between images with the old and new ITFs should at least have a reduction in the instrumental signal if it is due to ITF errors. It is also possible that the noise pattern could be maintained by a systematic misplacement in applying the ITF. Obviously the requirement of constancy in "systematic" is high, if this is the cause of such sharp signals.

Flat-fielding is necesary, of course, because of pixel by pixel sensitivity variations across the image. Under the general heading of these sensitivity variations, we mention as spectulation a type of noise which would be rigidly fixed to the camera location and would not be sensitive to temperature variation. Thompson (1984) investigated the variation in the location of the spectrum perpendicular to the dispersion as a function of wavelength, and found that it repeats strikingly from spectrum to spectrum. Irregularities in the fiber optics coupling between the ultraviolet converter (UVC) and the SEC tube may be responsible. Such irregularities might also be responsible for noise, distributing light unevenly on the camera. His results, however, do not demonstate variations on a pixel-by-pixel scale, as the noise pattern requires (Imhoff, 1987).

How can spurious velocity signals be avoided? The spikes can be recognized by their narrowness, and in many cases ignored. In addition it is sometimes desirable to remove them when they mask an interesting region of velocity space. For long wavelength spectra this can be done by cross-correlating images from both cameras or from two apertures, rather than two images from the same camera and the same aperture. For the short wavelength region different apertures can be used. Gaussian filtering suppresses the sharp signal, but does not remove it entirely.

The repetition of a pattern in the spectrum over a period of years found in the cross correlations would seem to be the kind of non-random noise which is present in IUE spectra, the "fixed-pattern noise". Flat-fielding on a pixel by pixel basis should in principle reduce noise from this kind of pattern, although a great deal of work would be needed to develop appropriate templates, investigate temperature sensitivity, and determine any other important variables.

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Table 1. Sharp Peaks

	Date	Aperture	LWR 12715	LWR 7008
LWR 9144	44538.52	SMAP	yes	yes
LWR 9149	44538.81	SMAP	yes	yes
LWR 9153	44539.03	LGAP	no	no

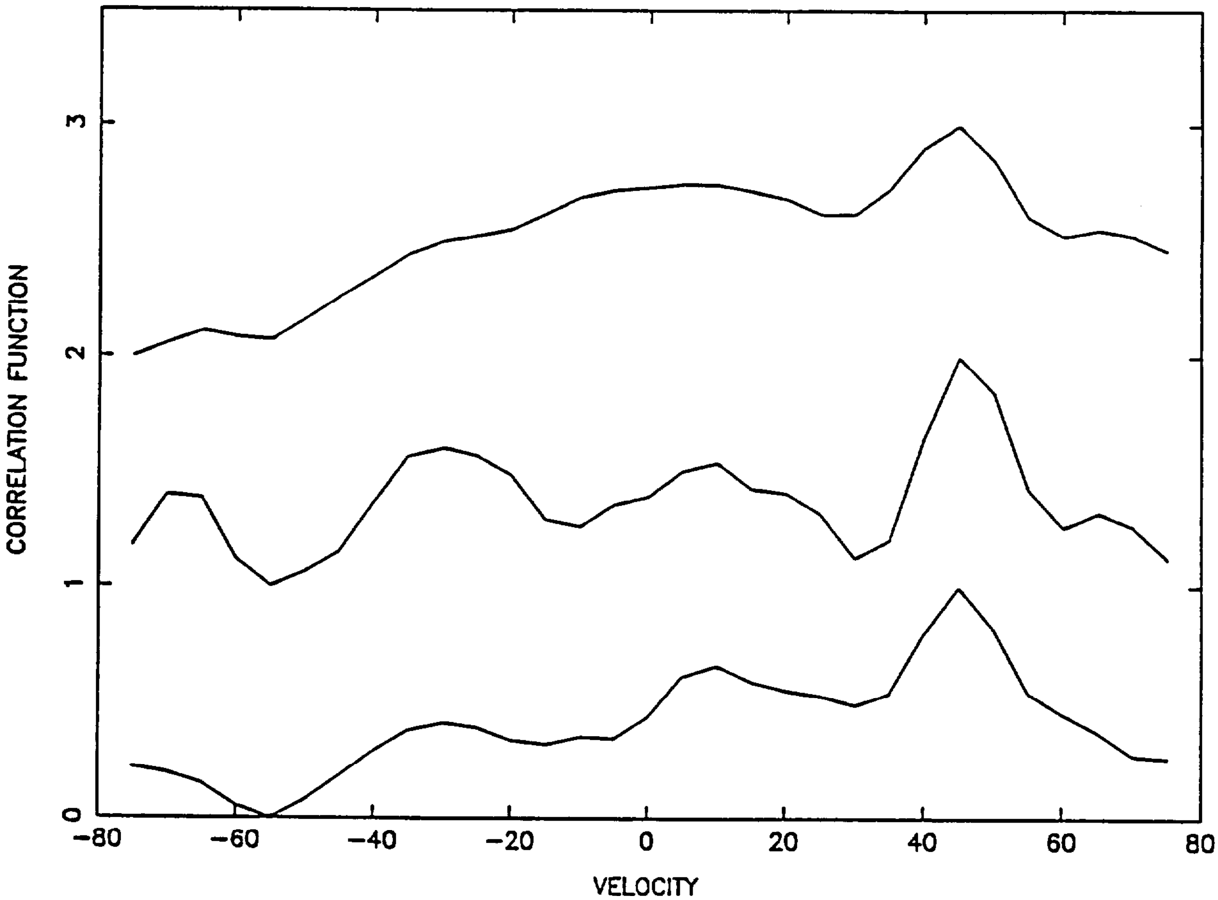

Figure 1. The cross correlation between η Aql (LWR 9149) and α Per (LWR 12715) for 3 orders covering the wavelength regions 2400 to 2420 Å (top), 2375 to 2390 Å (middle), and 2350 to 2360 Å (bottom). See text for discussion.

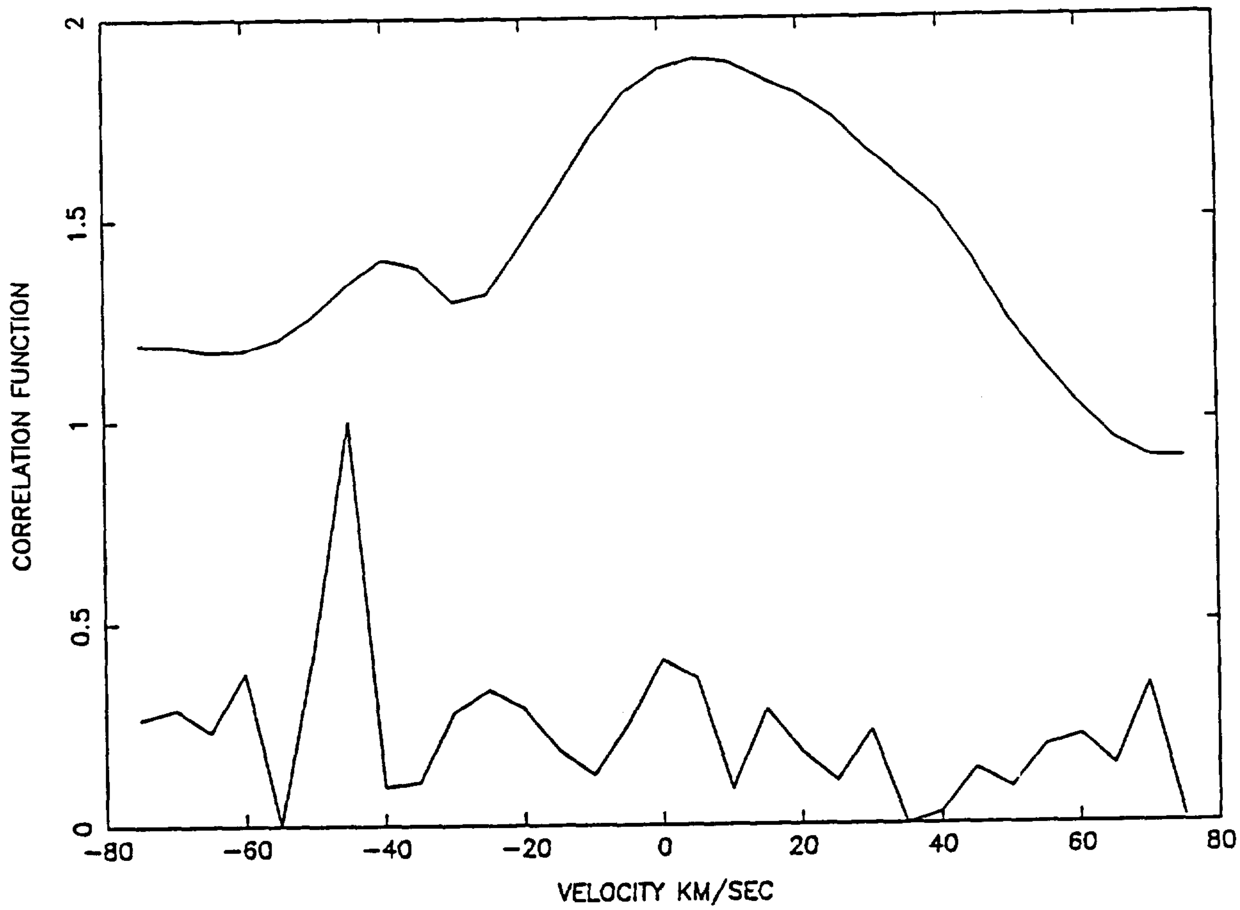

Figure 2. The cross correlation function for between α Per (LWR 12715) and α Lyr (LWR 7008) for order 94. The top shows the cross correlation of the stellar spectra; the bottom shows the cross correlation of the backgrounds.

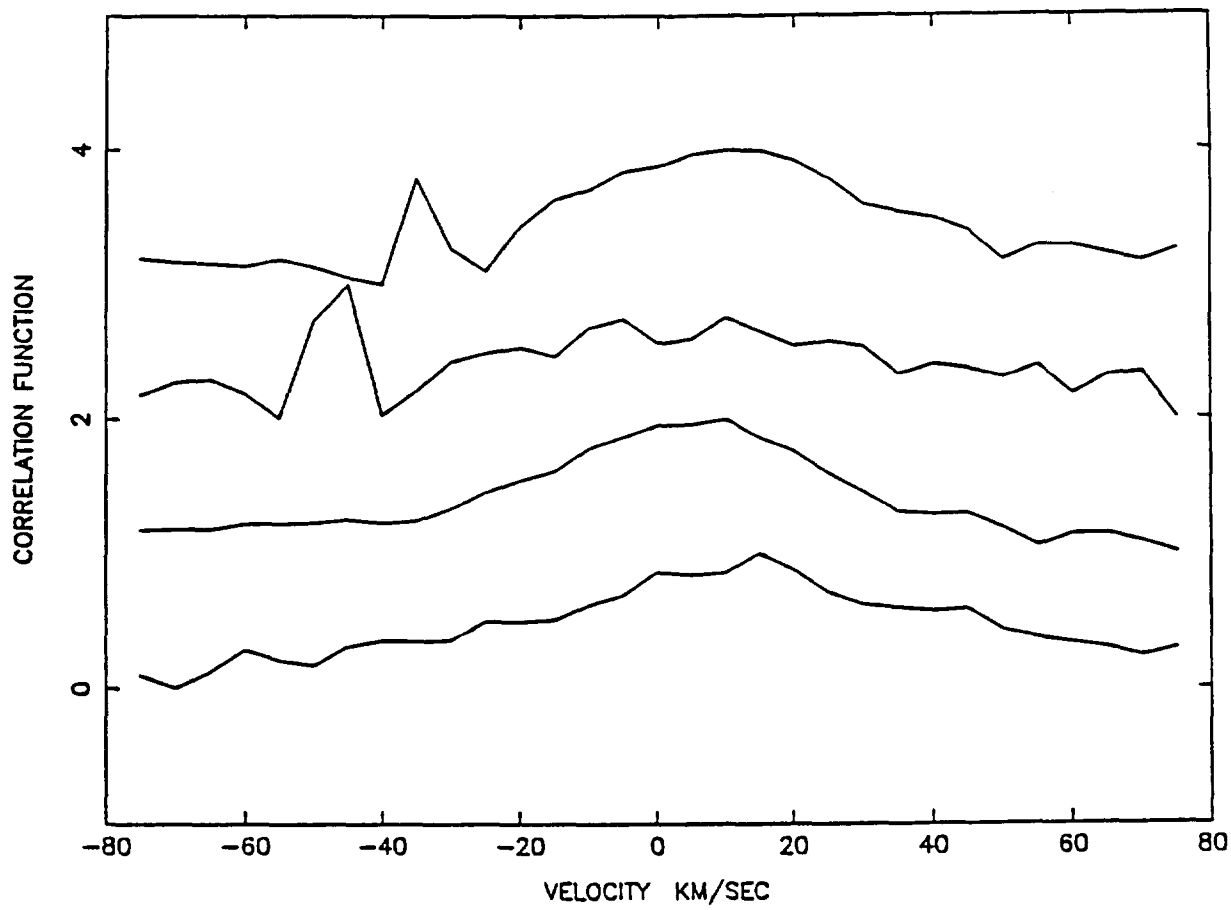

Figure 3. The cross correlation function (2420 to 2440 Å) of two pairs of spectra taken with the same long wavelength camera, and two pairs involving one spectrum from each camera. All spectra are small aperture spectra. The pairs are from top to bottom:

LWP 3009 α Per vs LWP 3008 α Lyr

LWR 12715 α Per vs LWR 7008 α Lyr

LWP 3009 α Per vs LWR 7008 α Lyr

LWR 12715 α Per vs LWP 3008 α Lyr