Removing the Pattern Noise from all *HST*/STIS Side-2 CCD data

Rolf A. Jansen (***rolf.jansen@asu.edu***)

School of Earth & Space Exploration and Department of Physics, Arizona State University, Tempe, AZ 85287-1404

[#344.11]

Abstract

When HST/STIS resumed operations in July 2001 using its redundant "Side-2" electronics, the read-noise of the CCD detector appeared to have increased by $\sim 1\,e^-$ due to a superimposed and highly variable "herring-bone" pattern noise. For programs aiming to detect signals near the STIS design limits, the impact of this noise is far more serious than implied by a mere $1\,e^-$ increase in amplitude of the read-noise, as it is of a systematic nature and can result in $\sim 8\,e^-$ relative deviations (peak-to-valley).

On this poster, I discuss the nature of the pattern noise, and summarize a method to robustly detect and remove this noise from raw STIS CCD frames (Jansen et al. 2003,2010; Brown 2001). I report on a Cycle 16/17 Archival Calibration Legacy program to remove the pattern noise from *all* raw, unbinned Side-2 STIS/CCD frames taken between 2001 July and 2004 August — representing a gain in effective sensitivity of a factor ~ 3 at low S/N. Pattern-free raw datasets, pattern-only images, and bias reference images are available from *http://stis2.sese.asu.edu/* .

A very similar pattern noise is present also in data taken after the successful repair of STIS during SM4. Presently public data (2009 June through 2011 October) were recently processed and are available from the same URL.

Nature of the Pattern Noise

The superimposed noise signal, due to analog-digital cross-talk or a grounding issue in the STIS Side-2 circuitry, is *not* a spatial signal, but a high frequency signal in time. That signal manifests itself as a spatial "herring-bone" pattern (Fig. 1) that drifts erratically — even during the relatively short time it takes to read the CCD. The pattern tends to be locally semi-coherent, however, and is best described as a modulated $\sim$14–18 kHz wave. The amplitude of that high-frequency wave is modulated by the superposition of three $\sim$1 kHz sinusoidal waves with phases that are shifted 120° from one another, and which have amplitudes of 3–5 e^- (see Fig. 2).

Since a 14–18 kHz frequency corresponds to a spatial period of 2.5–3.2 pixels, the values of adjacent pixels along a row tend to be affected by offsets of opposite signs (Fig. 2*a*), resulting in relative deviations of up to $\sim 8\,e^-$ (peak-to-valley). Adjacent pixels along columns experience offsets that are shifted in phase by amounts that vary from region to region in a single frame, and also from frame to frame. The resulting impact on Side-2 CCD data is therefore *far more serious* than implied by a mere $1\,e^-$ increase in the amplitude of the read-noise, and is partly *systematic* in nature.

Removing the pattern noise

Brown (2001) introduced a method to filter out the pattern noise by noting that the sequential charge shifts during read-out of the CCD allow one to convert a 2-D image into a timed signal. That time-series may be Fourier transformed to the frequency domain, where one can search for the frequencies responsible for the noise pattern, and then suppress them in various ways. This works well in images or portions of images where few bright and/or spatially very concentrated (sharp) features are present, but requires manual definition of the frequency limits of the filter. If the filter is chosen too wide, or if many genuine high-frequency non-periodic signals (e.g., stars, spectral lines, cosmic ray events) are present, ringing may occur.

Jansen et al. 2003 noted that the problem of automatically and robustly finding the frequencies that correspond to the pattern is *greatly* reduced if the genuine background and science signals are modeled and subtracted first. The resulting residuals image, ideally, only contains photon noise, read-noise, and the herring-bone pattern. In practice, since the model won't be (and does not need to be) perfect, there are systematic residuals of genuine features in the data as well. But the *contrast* of the herring-bone pattern has become *much* higher than in the original image. This means that, in the frequency domain, one can blindly run a peak finding routine with much relaxed contraints on the frequency interval (or alternatively on much poorer data — e.g., very long spectroscopic exposures that are riddled with cosmic ray hits) and still correctly find, fit, and filter out the pattern frequencies. Also, since most of the power from genuine signal has been removed prior to constructing the power spectrum, the problem of ringing is effectively avoided.

The method was further improved by replacing the power at frequencies associated with the noise pattern with white noise at a level and amplitude that matches the "background" power in two intervals that bracket the affected frequencies. In the original method, such frequencies were suppressed using multiplicative filters or windowing functions, or were set to zero. Replacement with white noise is less likely to introduce artefacts due to the absence of power at frequencies that should have some, or which may result when many adjacent frequencies have identical or zero power. The resulting modified power spectrum is inverse Fourier transformed, converted to a 2-D image, and added to the previously fitted "data model" to produce a CCD frame from which the pattern noise is *completely* removed.

This optimized Fourier filtering method, briefly outlined above and summarized in Fig. 3, was implemented in IDL procedure `autofilet.pro`. Several auxilliary shell-scripts provide input and allow batch processing of multiple CCD frames, while a compiled program generates multi-extension FITS datasets that are compatible again with `calstis`. A comparison of the pixel histograms of original and cleaned bias frames (Fig. 3*f*) demonstrates that the noise in the pattern-subtracted frames approximates the theoretically expected distribution very closely and *matches the nominal "Side-1" CCD read-noise that was observed prior to July 2001*.

Archival Calibration Legacy program AR 11258

As part of AR 11258, all raw, unbinned, full-frame Side-2 STIS/CCD data sets taken between 2001 July and the short in 2004 August (each containing one or more individual frames) were retrieved from the HST Archive and processed at ASU using `autofilet` to remove the herring-bone pattern noise. The 75345 cleaned frames were quality verified and merged back into 47192 multi-extension FITS (MEF) files and delivered to STScI. For each successfully cleaned frame, we logged the detected peak frequency, frequency drift width, and peak power for a trending analysis. Two examples are shown in Fig. 5. The removal of the pattern noise represents a gain in effective sensitivity of up to a factor ~ 3 at low S/N, if one uses superbias (Fig. 4) and superdark frames generated from pattern-cleaned frames in `calstis`.

All cleaned, pattern-free datasets (as well as pattern-only MEFs that may be subtracted frame by frame from raw data retrieved from the HST Archive) are available from: *http://stis2.sese.asu.edu/*

`Autofilet`, auxiliary software, and instructions are available from that URL or from the author.

Post-SM4 Side-2 STIS/CCD data

STIS was successfully repaired during the final HST Servicing Mission (SM4). Upon resuming Side-2 operations in June 2009, a very similar pattern noise remains present in all STIS/CCD data, with a slightly lower pattern frequency ($\sim$12–14 kHz), continuing a trend observed up till the short in August 2004, but with very similar amplitudes and driftwidths. Recently, all presently public data taken between 2009 June 2 and 2011 October 31 (30584 individual frames in 12958 datasets) were processed using `autofilet` and are now also available from: *http://stis2.sese.asu.edu/*

References

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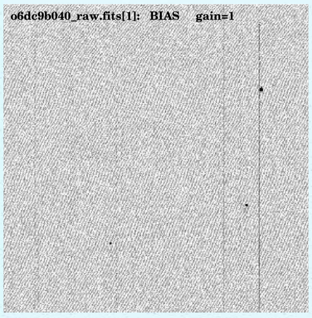

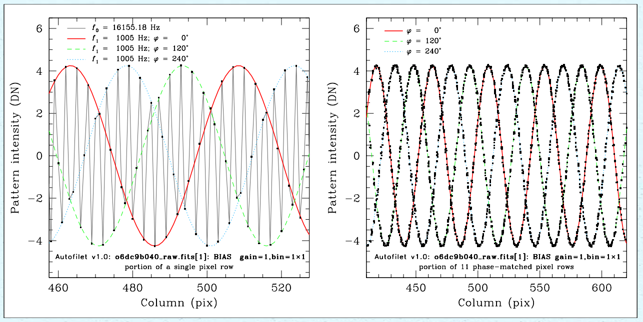

Fig. 1 [*left*] — A section of a raw, unbinned STIS/CCD BIAS frame taken in July 2001. *This section features the highly variable "herring-bone" noise pattern, several (vertical) columns and individual pixels with elevated bias level, as well as three regions affected by cosmic ray hits.*

Fig. 2 [*right*] — The pattern noise is *not* a spatial signal, but results from a high-frequency signal in time. *The difference of two adjacent pixels can be affected by up to $\sim 8\,e^-$ (peak-to-valley), and the pattern can be semi-coherent over tens to hundreds of pixels. Apart from the $\sim$16 kHz (2.8 pixel) pattern in this example, three sinusoidal waves — with a frequency of $\sim$1 kHz and phases that differ by 120° from one another — define an envelope on the amplitude of the high-frequency primary pattern. The $\sim$1 kHz signal is likely associated with an onboard oscillator or clock.*

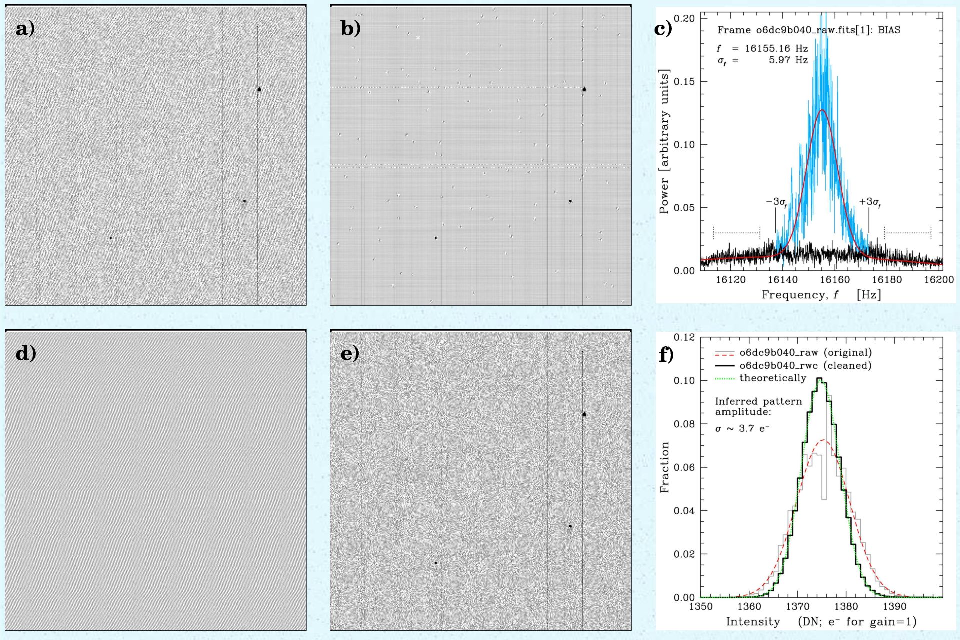

Fig. 3 — Overview of the **`autofilet`** procedure. *(a) Section of the raw STIS/CCD BIAS frame of Fig. 1. (b) A data "model" constructed for this section, containing most of the signal (as fitted to the image lines and columns) and also all pixels deviating from that fit by more than 3σ, or by more than 0.5σ when adjacent to a pixel that deviates by more than 3σ. The difference of the original image section and this model, i.e., the* residuals image, *is converted to a time-series and Fourier transformed to frequency space. (c) Portion of the power spectrum centered on the frequencies responsible for the herring-bone pattern. After finding the peak frequency, an estimate of its width (resulting from the erratic drift in frequency of the pattern during the time it takes to read the CCD) is obtained by fitting a Gaussian. All power within $\pm 3\sigma$ of the peak frequency is then replaced by white noise that matches the noise in the two bracketing regions located 4–7σ away. The resulting modified power spectrum is inverse Fourier transformed and converted back into a 2-D image, to which the model of panel (b) is added. (e) The resulting pattern-subtracted, cleaned frame. Note, that there is no "ringing" around bright regions affected by cosmic ray hits. The difference between panels (a) and (e), i.e., an image of the detected noise pattern, is shown in (d). (f) Comparison of the distribution of pixel values in the raw and pattern-subtracted BIAS frames. Whereas the noise in the raw BIAS frame is distinctly non-gaussian near the mean pixel value and has a $\sigma \sim 5.5\,e^-$, after removal of the inferred herring-bone pattern the remaining noise closely resembles white noise with a significantly smaller standard deviation $\sigma \sim 4.0\,e^-$.* **`Autofilet`** *therefore successfully reproduces the nominal "Side-1" CCD read-noise observed prior to July 2001.*

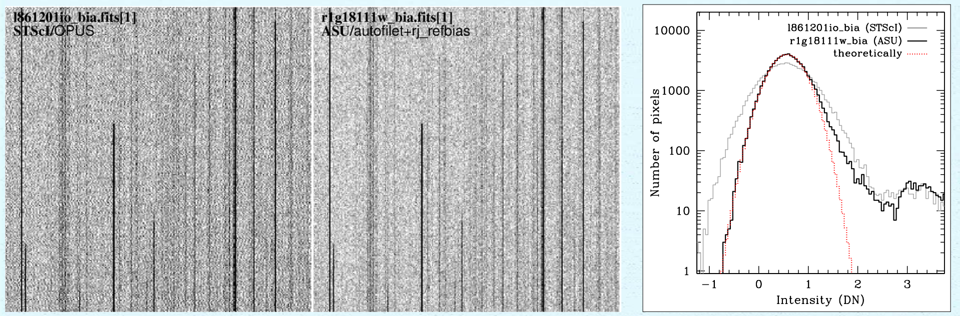

Fig. 4 — Comparison of a weekly "superbias" reference frame retrieved from the HST Archive and one constructed from pattern-subtracted biases. *While the "herring-bone" patterns vary from one frame to the next, they are not sufficiently random to cancel out completely when averaging multiple frames. In the left panel, significant residuals from the pattern noise are seen even when more than 100 individual frames are averaged. The frame constructed from our pattern-subtracted biases (middle) is free of such residuals. Indeed, in the right panel, the pixel histogram of the STScI/OPUS bias reference frame shows a broader distribution of pixel values, while our frame approximates the theoretically expected gaussian distribution. The observed tail toward higher pixel values results from hot and warm pixels, mostly located along discrete detector columns.*

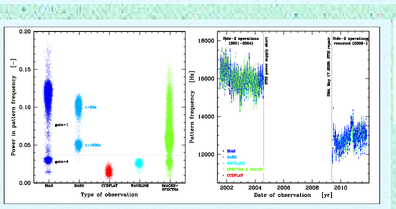

Fig. 5 — Noise pattern trends. **[*left*]** *Detected peak power in the frequencies associated with the "herring-bone" pattern noise. The DARKs show that pattern detection contrast depends on the spatial density of genuine (or cosmic ray induced) strongly peaked signals.* ***[right]*** *The average frequency associated with the pattern noise decreased by $\sim$6% from 2001 July through 2004 July. The pattern frequencies observed after the successful repair of STIS during SM4 roughly match a continuation of that trend. At any given epoch there is a wide range of $\sim$1–3 kHz in pattern-frequency measured in individual CCD frames, but frames taken in close succession tend to show similar pattern-frequencies. Some of the larger excursions in frequency may be associated with monthly anneals.*

Acknowledgements

Most of this work was funded by grants HST-AR-11258 and HST-GO-9066 from STScI, which is operated by AURA under NASA contract NAS5-26555. The author thanks R. Windhorst, H. Kim, N. Hathi, P. Goudfrooij, N. Collins, C. Proffitt, B. Whitmore and Bruce Woodgate, and especially acknowledges the prior work by T.M. Brown.