SIGNAL-TO-NOISE RATIOS IN IUE SWP-LO SPECTRA OF CHROMOSPHERIC EMISSION-LINE SOURCES

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ABSTRACT

The short-wavelength-prime (SWP) detector of the International Ultraviolet Explorer should operate near the photon-counting limit, but the noise levels in flat-field images are several times higher. The exaggerated noise can be traced to the incomplete removal of the pixel-to-pixel granularity of the television frames by the prevailing Spectral Image Processing System. An empirical noise model for the current-epoch photometric linearization strategy and one for a hypothetical processing system that achieves complete flat fielding of the raw images are derived. A formula is then proposed to predict the signal-to-noise ratio in the measured flux of an emission line—possibly superimposed on a smooth continuum—in an IUE low-dispersion (5 Å resolution) far-ultraviolet (1150 Å–1950 Å) spectrum as recorded with the SWP camera. For illustration, I specialize the formula to the important C IV λ1549 feature of F–K stars. The S/N relation permits one to determine sensitivity limits, upper limits in faint exposures, and optimum exposure times.

Key words: stars: late-type—spectra: ultraviolet—instrumentation: detectors

1. Introduction

Astronomical spectroscopy with the International Ultraviolet Explorer requires accurate exposure times. Exposures too short can result in faint or blank images; those too long can waste precious observing shifts and might yield saturated spectra as well. In spite of the long history of the IUE mission, however, to my knowledge no one has carried out a detailed study of optimum exposure times from first principles. Most observers simply rely on their own experience with the same, or similar, targets or blithely apply the inverse-sensitivity curves published in the Proposal Preparation Guide (which are useless for faint sources).

The lack of a quantitative relationship between exposure times and expected signal-to-noise ratios prevents accurate assessments of the minimum fluxes to which the IUE can be pushed, or the related issue of the proper evaluation of upper limits in deep exposures of faint objects. Further, the advent of new ultraviolet-capable instruments like those of HUBBLE raises the critical question: "Is it entirely not feasible to obtain a particular ultraviolet spectrum with the IUE?"

In order to resolve these issues I have examined the sources of noise in the prime detector (SWP camera) of the short-wavelength spectrograph of the IUE: It provides access to the important far-ultraviolet region (1150 Å–1950 Å), particularly in the sensitive low-dispersion mode (5 Å resolution). Working from the resulting noise model, I propose a formula to predict signal-to-noise (S/N) ratios in IUE low-dispersion spectra. I specialize it to the important practical case of chromospheric emission-line stars (e.g., Jordan and Linsky 1987), but the method can be generalized to any cosmic source.

2. The SWP Camera

The signal-to-noise ratios of IUE low-dispersion spectra must be traceable to the fundamental properties of the Intensified Secondary Electron Conduction (ISEC) cameras utilized in the tandem spectrographs. Although the ISEC systems are considered antiquated compared with modern charge-coupled devices, the vast archive of IUE images (some $10^5$, to astrophysical accuracy) provides a strong motivation to understand their operation.

An overview of the IUE detectors has been given by Harris and Sonneborn (1987); additional details concerning their technical properties can be found in the Camera Operations Manual (Ward 1977) and the Camera Users' Guide (Coleman and Snijders 1977). The salient points are summarized below.

The television tubes of the IUE cameras are visible-light devices. Thus, the ultraviolet image from the spectrograph first is translated into a visible-light replica by a proximity-focused intensification stage with a phosphor-coated output screen (the Ultraviolet-to-Visible Con-
verter). A fiber-optic coupler transfers the blue image to the window of the SEC tube, where it impinges on the bialkali cathode of the camera. The liberated photoelectrons are accelerated through a potential difference of \( \approx 5 \) keV and bombard a potassium chloride target. Secondary electrons dislodged in the insulating target migrate toward a conducting signal plate under the influence of an internal electric field. The exposed positive-charge image subsequently is scanned by a Vidicon-type pulsed electron gun, and the signal is digitized as an 8-bit (0–255) telemetry word (a Data Number or DN) by a video analog-to-digital converter. Following the destructive readout cycle, the camera is prepared for the next exposure by flooding it via a bank of tungsten filament flash lamps and discharging the overexposed image with additional scans of the read beam.

The intensified-Vidicon camera was favored for the IUE application because the small thermionic emission rates of its (two) photocathodes and highly insulating target permit long integration times. Furthermore, the additive component of the system noise is essentially negligible ( \( \approx 1 \) DN rms as measured beyond the target ring).

Over the interval of counts where the photometric response is linear, the output DN scales directly as the integrated photoelectron production per pixel (at the photocathode of the image intensifier). The photoelectron yield, in turn, is related to the incident ultraviolet intensity through the quantum efficiency (QE) of the cesium-telluride photocathode, about 15% over most of the ultraviolet range.

The proportionality constant, \( \gamma \), between output counts and first-stage photoelectrons is established by the multiplication factors in the two acceleration stages and the electronic gains and biases of the amplifiers and analog-to-digital converter. Coleman and Snijders (1977) cite a \( \gamma \)-factor for the SWP camera of about 1.1 DN ( \( e^- \)) pixel\(^{-1} \) when it is exposed and scanned using the default settings for normal Guest Observer observations. However, the effective \( \gamma \) varies spatially across the video frame owing to a large-scale asymmetry in the performance of the television tube, a fault concentrated mostly in the target and scanning assemblies.

Ideally the noise in the output signal would be dominated by the Poisson statistics of the incident ultraviolet photons, but practical detectors fall short of that ideal. If one defines a total system efficiency, \( \varphi \), to be the ratio of output counts, \( \mathcal{C} \), to input photons \( N \) (per pixel), it is easy to show that the output noise in counts is

\[
\sigma_C = \sqrt{\mathcal{C}} \times \left[ \varphi + \frac{N}{2} \sigma_0^2 \right]^{1/2}.
\]

The product of the leading term and the first term in parentheses ( \( \varphi \approx 2 \sqrt{N} \)) is simply the uncertainty in the output counts corresponding to the intrinsic uncertainty of the incident photon number ( \( \sqrt{N} \)). The second term accounts for the additional statistical noise introduced by the detector system itself. Here \( \sigma_0 \) is defined as the uncertainty in the output counts divided by the output counts for a specific input photon number \( N \). The broader the system response, the more its noise will dominate the counting statistics of the input radiation; the sharper the response, the closer the detector will operate to the photon-counting limit. On the one hand, note that the output noise will scale as the square root of the output signal if the system response is relatively Gaussian (so that \( \sigma_0 = \sigma_0/\sqrt{\mathcal{C}} \), where \( \sigma_0 \) is independent of \( N \)). On the other hand, note that the proportionality constant need not be unity, contrary to the widespread belief that the minimum counting noise of a photon detector is given by the square root of the number of detected photons. Ideal performance with the SWP camera, where \( \varphi = 0.15 \), implies a minimum noise of about 5 DN for an output signal of 200 DN.

Hypothetical behavior aside, one establishes the true signal-to-noise characteristics of a detector system by evaluating representative test images, preferably flat fields. One recent study of photometrically corrected (and spatially resampled) SWP low-dispersion spectra by Kinney, Bohlin, and Neill (1988) suggests rms noise levels some 2–3 times the limiting value predicted by photon statistics. Furthermore, an investigation of highly processed (photometrically linearized and spatially extracted) SWP echellograms by Leckrone and Adelman (1989) indicates a disturbingly high level of non-Poisson “fixed-pattern” noise.

However, the procedures used to create the processed spectra evaluated by Kinney et al. and Leckrone and Adelman can introduce additional noise (or, in some cases, suppress the intrinsic noise). Therefore, I decided that it would be worthwhile to examine a representative sample of unprocessed (“raw”) flat-field images taken with the SWP camera in order to explore its noise characteristics at a more fundamental level.

3. Empirical Measurement of Noise in SWP Flat Fields

Table 1 summarizes the SWP images evaluated in the present study. There are three general types. First is a sample of about 50 SWP flat-field exposures (mercury pen-ray lamp, tungsten filament lamp, and null images), most of which were taken by the IUE Resident Astronomers in early 1985 during a recalibration of the camera (in particular its so-called Intensity Transfer Function (ITF)). The second type are six long-duration ( \( t_{exp} \approx 700 \) minutes) “sky” exposures which record primarily accumulated camera backgrounds. The third type are low-dispersion spectra of the bright chromospheric sources \( \alpha \) Aurigae and \( \alpha \) Canis Minoris, which have had
TABLE 1
IUE SWP Images

<table>
<thead>
<tr>
<th>Image Type</th>
<th>$t_{\text{exp}}$ (m:s)</th>
<th>THDA °C</th>
<th>SWP Image Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>NULL</td>
<td>0:00</td>
<td>9.4 ± 0.3</td>
<td>25012 25050 25088 25126 25150</td>
</tr>
<tr>
<td>40% UVL</td>
<td>1:13</td>
<td>9.2 ± 0.3</td>
<td>25020 25058 25075 25098 25111</td>
</tr>
<tr>
<td>80% UVL</td>
<td>2:26</td>
<td>9.1 ± 0.3</td>
<td>25026 25056 25093 25101 25135</td>
</tr>
<tr>
<td>100% UVL</td>
<td>3:02</td>
<td>9.0 ± 0.2</td>
<td>25015 25019 25024 25029 25054</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>25059 25064 25092 25094</td>
</tr>
<tr>
<td>130% UVL</td>
<td>3:57</td>
<td>9.2 ± 0.3</td>
<td>25021 25060 25072 25097 25146</td>
</tr>
<tr>
<td>200% UVL</td>
<td>6:04</td>
<td>9.1 ± 0.2</td>
<td>25025 25068 25095 25106 25112</td>
</tr>
<tr>
<td>280% UVL</td>
<td>8:30</td>
<td>9.1 ± 0.3</td>
<td>25014 25057 25071 25108 25140</td>
</tr>
<tr>
<td>340% UVL</td>
<td>10:19</td>
<td>9.1 ± 0.3</td>
<td>25022 25065 25096 25105 25147</td>
</tr>
<tr>
<td>210% TFL</td>
<td>0:16</td>
<td>9.2 ± 0.0</td>
<td>25032 25033 25035 25036</td>
</tr>
<tr>
<td>375% TFL</td>
<td>0:32</td>
<td>9.5 ± 0.0</td>
<td>25040 25041 25043 25044</td>
</tr>
<tr>
<td>SKY</td>
<td>800 ± 70</td>
<td>10.8 ± 2.2</td>
<td>20020 21216 23679 23687 29840</td>
</tr>
</tbody>
</table>

short (up to 3.3 s) tungsten lamp flat-field exposures superimposed on the stellar spectrum for technical reasons to be described below. Of interest for the moment is the first group.

The flat-field images of the undispersed $\lambda 2500$ mercury discharge radiation provide the fundamental calibration of the SWP camera with respect to the granularity of the pixel-to-pixel sensitivity of the system response $2$. Because the quantum efficiency of the first-stage photocathode is high at 2500 Å, the mercury lamp flat fields should contain a noise contribution due to the photon fluctuations in the incident light in addition to the system noise (cf. eq. (1)).

I collected from the raw-image archive at least five mercury lamp images ("UVL") for each of eight representative exposure levels (nine images for the "100%" level (maximum DN of $\approx 170$)) taken during the 1985 recalibration campaign. I measured the mean DN levels and the rms variances of the individual images of each set in $32 \times 32$ pixel$^2$ boxes centered at the image coordinates corresponding to the wavelength range 1200 Å–1900 Å (in 100 Å intervals and at 1550 Å) for the spectrum of a point source centered in the $10'' \times 20''$ large aperture. Figure 1 illustrates the geometry.

In practice I fitted a least-squares Gaussian to the histogram of pixel intensities to determine the mean count level and rms variance of each $32 \times 32$ subimage. The subimages were then scaled to the average DN of the set and coadded. A Gaussian was fitted to the pixel histogram of the coadded subimage to determine the granularity of the flat field at that particular spatial position in the video frame. Next, I constructed an array of the image-to-image rms’s—the variance of the normalized intensities over the five flat fields of a set—as a function of pixel position. Again, a Gaussian was fitted to the histogram of the pixel rms’s in the “variance” subimage.
TABLE 1 (cont’d)

<table>
<thead>
<tr>
<th>Image Type</th>
<th>$t_{\text{exp}}$</th>
<th>THDA (m:s)</th>
<th>°C</th>
<th>SWP Image Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other Flat-Fields [1986–1987]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>101% TFL</td>
<td>0:08.5</td>
<td>7.8 ± 0.0</td>
<td>31953</td>
<td>32003</td>
</tr>
<tr>
<td>42% TFL</td>
<td>0:03.3</td>
<td>6.8 ± 0.0</td>
<td>27755</td>
<td>27756</td>
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<tr>
<td>Stellar SWP-LO’s [1986.1]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\alpha) Aur$^b$</td>
<td>3x3:20</td>
<td>8.6 ± 1.3</td>
<td>27681</td>
<td>27700</td>
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<td>27718</td>
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<td>27764</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>27813</td>
<td>27835</td>
</tr>
<tr>
<td>(\alpha) CMi$^b$</td>
<td>3x3:20</td>
<td>9.0 ± 1.1</td>
<td>27694</td>
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<td>27720</td>
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<td>27770</td>
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<tr>
<td></td>
<td></td>
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<td>27836</td>
<td>27837</td>
</tr>
</tbody>
</table>

Notes:

"THDA" is the SWP temperature as recorded by a thermister on the camera-head amplifier; "UVL" is a flat-field exposure of the mercury discharge lamps; and "TFL" is a flat-field exposure of the tungsten filament flash lamps.

$^a$SWP-LO spectra of \(\alpha\) Aur on which are superimposed 3.3-s TFLs as part of a radiation-background compensation scheme (see text).

$^b$Other SWP-LO spectra were taken during the monitoring campaign, but only the 3 x 3:20 (triple) exposures were analyzed for the present study. See Ayres [1990] for additional details.

to establish the average random noise in the flat fields at that spatial position.

Figure 2 summarizes the results for the eight mercury lamp exposure levels at three representative locations in the image frame. The apparent granularity ranges from about 5%-15% of the signal, with a monotonic dependence on spatial position (giving the appearance of an increase with decreasing wavelength.) The rms noise among the flat fields is uniformly low, ranging from 2%-5% of the signal, again smoothly varying along the low-dispersion extraction stripe. Near the center of the tube at position \(\beta\) (corresponding to 1550 Å), the apparent intrinsic noise levels are remarkably close to those predicted by the Poisson model given the nominal operating parameters of the SWP camera cited by Coleman and Snijders (1977). As far as the mercury lamp flat fields are concerned, the SWP camera operates near the photon-noise limit, and the system response must be relatively sharp.

4. Other Sources of Noise in IUE Images

Unfortunately, what applies to flat-field images of the
Fig. 1—Schematic view of an IUE SWP image illustrating the 32 × 32 pixel areas along the low-dispersion extraction stripe where mean count levels and variances were measured. Three specific positions, designated α, β, and γ, are referenced in Figure 2, below. The areas intentionally are not described in terms of the equivalent wavelengths (1300 Å, 1550 Å, and 1900 Å, respectively) to emphasize that the signal-to-noise evaluations were performed on flat-field images exposed to undispersed longer wavelength light (either λ2500 radiation from a mercury discharge tube or visible light from a bank of tungsten filament lamps). The small filled squares represent fiducial (reseau) marks.

The SWP camera is sensitive to visible light through a weak (QE ~ 10⁻³ – 10⁻⁴) tail of the sensitivity of the first-stage photocathode.

mercury discharge lamps does not necessarily apply to spectra of celestial sources. One potential problem is the degree to which the photometric linearization is achromatic. That is, how well do the 2500 Å monochromatic images flatten the pixel-to-pixel granularity at other wavelengths? One can easily imagine, for example, that the 1200 Å response of the first-stage photocathode has somewhat different spatial variations than the 2500 Å response, owing, for example, to wavelength-dependent differences in optical interference effects, penetration depths, and photoelectron escape probabilities in the thin cesium-telluride layer.

The issue is crucial because the important source of background fogging by cosmic particle radiation arises largely from the production of Cerenkov light in the magnesium-fluoride faceplate of the camera: That portion of the Cerenkov spectrum which falls in the visible might produce a different granularity of the background than appears in the mercury lamp flat fields. Furthermore, the low-level dark emission of the dual photocathodes (mostly contributed by the second stage) need not have the same effective pixel-to-pixel response as that produced by the absorption of ultraviolet photons. The accumulated dark emission (and a usually smaller background due to “afterglow” in the P-11 phosphor of the intensifier) becomes critically important in long exposures of faint spectra.

Fig. 2—Summary of the mean intensities and variances measured in a sample of SWP flat-field images. Panel (a) depicts the granularity of mercury lamp calibration images (UVL) at three reference positions (see Fig. 1) as a function of exposure level (in the convention adopted by the IUE Resident Astronomers: a “100%” exposure ranges from 90 DN at location α to 170 DN at location γ. “0%” is a null image). The granularity was determined by coadding five independent images at each exposure level and measuring the pixel-to-pixel rms in the composite. The curves are least-squares parabolas of the pseudo-Poisson noise model described in the text. The thin shaded curve near the bottom of the panel indicates the DN expected for photon-noise-limited performance of the SWP detector given its nominal operating parameters (although in reality there is a large-scale asymmetry in the performance of the tube, e.g., from position α to γ). Panel (b) is analogous to panel (a) for the intrinsic random noise component. Here, σ<sub>DN</sub> was determined by measuring the rms variance among the five UVL images of an exposure set at each pixel position, then calculating the mean of the σ's in the 32 × 32 reference areas. These variations, on top of the systematic pixel-to-pixel granularity, likely arise partly from the photon statistics of the incident ultraviolet light (from mercury discharge lamps) and partly from device-specific sources. The true system noise levels clearly are much smaller than the granularity and approach the ideal of photon-limited performance desired in a low-light-level detector. Panel (c) illustrates the results of noise measurements in representative production-processed photometrically corrected tungsten lamp (TEL) and sky-background images. (One of the position γ measurements was deleted because the 42% TEL was, in fact, superimposed on a stellar spectrum, and the source continuum strongly contaminates the long-wavelength portion of the frame). Although the photometric linearization procedure in principle should remove the granularity, in practice it does not (for technical reasons discussed in the text). The elimination of that “rectification noise” would substantially improve the quality of SWP-LO spectra.
sources. If the background is not properly flat fielded, then the intrinsic noise levels in the superimposed spectrum will be compromised by residual granularity. It potentially is a large effect. In the mercury lamp images the pixel-to-pixel sensitivity variations are 2–3 times the intrinsic noise.

A related, but minor, problem is the “fixed-pattern” noise that results from the fact that the photometric linearization tables are constructed from a finite number of flat-field images. Because five or more mercury lamp images are combined for each level of the ITF, the fixed pattern should be smaller by a factor of $\approx \sqrt{5}$ than the random noise in an individual image. Thus, the fixed pattern will not manifest itself unless one coadds $\approx 5$ spectra taken under identical circumstances.

A variant of the fixed-pattern noise is the possibility that the granularity changes nonlinearly over the $\approx 20$ DN separating the 12 discrete levels of the photometric linearization function. If so, the linear interpolation of the ITF tables will not properly flatten an intermediate-valued pixel.

Another source of noise related to granularity is “misregistration noise”. It results from the application of the linearization function to the “wrong” pixels, owing, for example, to small distortions of the camera format at extreme operating temperatures. The IUE cameras do not have physical pixels like modern electronic sensors, but the pixels are determined by the trajectory of an electron beam. Thus, the pixel locations with respect to the granularity of the photocathodes and SEC target can shift slightly as external conditions are changed. Simply displacing a flat-field image with respect to itself by as little as one pixel can result in a complete decorrelation of the apparent granularity. Fortunately, the thermal shifts of the SWP camera are small ($= 0.1$ pixel C$^{-1}$; Turnrose and Thompson 1984).

A more insidious form of pixel shifting can result from “beam-pulling”, the tendency of heavily exposed (and thus heavily charged) regions of the target to draw the read beam slightly off course and therefore discharge a slightly different physical area of the target than intended for that particular scan line and sample number. Beam-pulling will manifest itself most in images with heavy overexposures, large spatial gradients in intensity (e.g., far-ultraviolet emission spectra of late-type stars), or high backgrounds (owing to the contrast during scanning between the already-discharged and still-charged portions of the target). In the worst case, the linearization procedure will completely fail to flatten the pixel-to-pixel granularity of the spectrum and the resulting “misregistration noise” will be several times the intrinsic noise.

Yet another source of noise can result from any effective smoothing of the granularity of the photometric linearization functions that accompanies their application to production images. For example, in the present version of the Spectral Image Processing System the ITF tables are created by first geometrically correcting the mercury lamp images, then coadding them. The geometrical rectification compensates for the small thermal shifts of the calibration images taken at different camera temperatures. However, the photometric linearization is applied to unrectified (“raw”) production images by subjecting the ITF tables to the inverse geometrical transformation taking into account the temperature of the particular science image. The two geometrical transformations (one to build the ITFs, one to apply them) smooth out the true pixel-to-pixel granularity (e.g., Bohlin 1988). Thus, some of the intrinsic granularity of the raw images survives the linearization procedure and contributes to the apparent noise levels: One might call it “rectification noise”. It is believed to be the dominant source of pixel-to-noise rms noise in currently processed IUE spectra (e.g., Harris and Sonneborn 1987; Linde and Dravins 1988), and its elimination is the major focus of the so-called Final Archive Definition Committee (e.g., NASA IUE Newsletter, No. 36).

5. Evaluation of Relative Importance of the Several Noise Sources

I evaluated the relative importance of the aforementioned noise sources as follows.

5.1 Chromatic Deviations

To judge how chromatic the ITF pixel-to-pixel correction is, I flattened two sets of four tungsten lamp images (“TFL”), taken in the 1985 recalibration campaign, against themselves and against the sets of mercury lamp images of comparable exposure level. The tungsten flood lamps emit virtually no flux in the vacuum ultraviolet: The SWP camera responds to their visible emission through the extended tail of the first-stage quantum efficiency.

The tungsten lamp flat fields were taken in a narrow range of temperature coincident with that of the mercury lamp images ($9.2^\circ \text{C} \pm 0.3^\circ \text{C}$); thus, any relative shifts should be negligible. Both the “210%” and “375%” TFL sets were successfully flattened by the 200% and 340% UVL sets, respectively: The pixel-to-pixel rms’s of the ratio images were comparable or somewhat smaller than those at the same wavelengths of the self-flattened mercury lamp set. I conclude that the granularity of the ITFs are relatively achromatic, at least between 2500 Å and the visible.

Incidentally, the gross spatial distributions of mean counts in the comparable mercury lamp and tungsten lamp images are distinctly different, indicating that a properly photometrically linearized tungsten lamp flat field might be relatively smooth but it will not be truly flat. The asymmetry possibly arises from a difference in illumination angles between the two sets of lamps and potentially could affect high-background production images.
5.2 Nonlinearities in the ITF

To test the possible influence of interpolations between different levels of the ITF, I ratioed the five 80% UVLs and five 130% UVLs against the five best (closest in mean DN) 100% UVLs. The flattening was successful, indicating that neighboring levels of the ITF can remove each other's granularity.

5.3 Beam-pulling

Unfortunately, I do not have any reliable means to test the extent to which beam-pulling compromises the photometric linearization procedure. Thus, for want of hard evidence to the contrary, I optimistically will assume that it is not a significant source of noise in normal IUE spectra.

5.4 Registration Errors

To test the influence of misregistration noise, I attempted to flatten two 8.5-s tungsten lamp images (equivalent to a 101% UVL), both acquired at comparatively low temperature (7.5° C), against the five best 100% mercury lamp exposures (9.0° C ± 0.2° C). The effective thermal shift between the images would be a few tenths of a pixel according to the models cited by Turnrose and Thompson (1984). In contrast to the previous comparisons, here the flattening was less successful: The pixel-to-pixel rms was reduced only about 30% over most of the short-wavelength range, compared with a factor of 2–3 seen in the self-flattening of the mercury lamp images, and actually increased at position γ. The comparison emphasizes the importance of applying the photometric linearization to the correct pixels: Even subpixel shifts can dramatically increase the apparent noise levels (as shown for the LWR camera by Linde and Dravins (1988)).

5.5 Rectification Errors

Finally, I assessed the magnitude of rectification noise by evaluating the S/N levels in the photometrically corrected images (current-epoch processing) of the two 8.5-s tungsten lamp flat fields, two of the low-dispersion spectra of α Aur with backgrounds dominated by 3.3-s TFLs, and one 840-m sky-background exposure (courtesy E. W. Brugel). I measured the mean signals and rms noise levels in the linearized “flux numbers” of the processed images. I estimated the equivalent σDN by multiplying (S/N)F−1 by DN − DN0, where DN is the mean signal level in the corresponding raw image, to account for the DN0 ≈ 10–25 null levels against which the flux number scale is defined. Panel (c) of Figure 2 illustrates the results. The noise values in the photometrically linearized images are comparable to the pixel-to-pixel granularity itself, suggesting that it was not removed successfully by the production ITF tables. As speculated by Harris and Sonneborn (1987) it appears that SWP spectra reduced with the prevailing software are dominated by processing noise rather than the intrinsic noise of the detector system. I have every reason to believe that this unfortunate situation will be rectified soon by the efforts of the IUE Project for the Final Archive.

6. Noise Model for SWP-LO

Both the rms granularity and the random noise levels of the mercury lamp exposure sets depicted in Figure 2 can be fitted to a pseudo-Poisson model:

\[ \sigma_{DN} = \alpha \times (DN - DN_0)^{1/2}, \]

where the scale factor \( \alpha \) and the null level DN0 are functions of camera position. Table 2 lists the null levels and \( \alpha \) values (\( \alpha_{\text{max}} \) for the granularity and \( \alpha_{\text{min}} \) for the intrinsic noise) that were derived from the analysis of the mercury lamp flat fields.

Realistically, no practical production processing system will realize complete flat fielding of highly structured far-ultraviolet spectra like those of chromospheric emission-line sources. Nevertheless, it is not unrealistic to expect that the final archive system will achieve at least partial compensation for the pixel-to-pixel granularity. Thus, the effective \( \alpha \) will lie somewhere between the minimum value characteristic of the intrinsic noise between similarly exposed calibration flat fields and the maximum value characteristic of the pixel-to-pixel sensitivity variations. For the sake of illustration in what fol-

### Table 2

<table>
<thead>
<tr>
<th>Position^a (Å, DN)</th>
<th>Wavelength (Å)</th>
<th>DN0 (DN)</th>
<th>( \alpha_{\text{max}} )</th>
<th>( \alpha_{\text{min}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(166, 407)</td>
<td>1200</td>
<td>12.6</td>
<td>1.49</td>
<td>0.49</td>
</tr>
<tr>
<td>(206, 360)</td>
<td>1300</td>
<td>13.2</td>
<td>1.55</td>
<td>0.53</td>
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<tr>
<td>(244, 316)</td>
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<td>13.8</td>
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<td>14.9</td>
<td>1.14</td>
<td>0.49</td>
</tr>
<tr>
<td>(324, 225)</td>
<td>1600</td>
<td>16.0</td>
<td>0.95</td>
<td>0.47</td>
</tr>
<tr>
<td>(362, 180)</td>
<td>1700</td>
<td>17.7</td>
<td>0.77</td>
<td>0.42</td>
</tr>
<tr>
<td>(400, 135)</td>
<td>1800</td>
<td>19.6</td>
<td>0.74</td>
<td>0.33</td>
</tr>
<tr>
<td>(440, 090)</td>
<td>1900</td>
<td>25.2</td>
<td>0.63</td>
<td>0.26</td>
</tr>
</tbody>
</table>

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^a \( \sigma_{DN} \approx \alpha \times (DN - DN_0)^{1/2} \).

^b (LINE, SAMPLE) coordinates in raw image.
The signal in an IUE low-dispersion spectrum of, say, a chromospheric emission-line source is the DN deposited by the feature of interest less a background contributed partly by the camera and partly by the source. Schematically

\[ DN = DN_{L} + DN_{C} + BKG + DN_{0}, \]

where the first term is the time-integrated fogging due to an emission line, the second term is that due to an underlying broad-band continuum (plus scattered light), the third term is that due to "backgrounds" unrelated to the stellar source, and the fourth term is the null level. Cosmic particle radiation provides the background in short exposures taken during NASA second shifts (US2). In longer exposures during low-radiation periods, the background is dominated by photocathode dark emission (1.5–4.5 DN h\(^{-1}\); Coleman and Snijders 1977) and afterglow in the P-11 phosphor of the intensifier (usually \(\approx 1\) DN h\(^{-1}\), but possibly higher following overexposures).

The signal-to-noise ratio for a pixel in an emission feature is

\[ S/N = \frac{DN_{L}}{\sigma_{DN}} \approx \alpha^{-1} \left( 1 + \left( \frac{DN_{C} + BKG}{DN - DN_{0}} \right) \right), \]

if the subtractions of the stellar continuum and camera backgrounds are "noiseless" (i.e., they are determined by averages over many pixels). The relation emphasizes that the effective S/N for a pixel in a spectral feature always will be less than that determined from statistical evaluations of flat-field images exposed to the same peak DN.

8. S/N for the Integrated Line Flux

That is by no means the whole story. An emission line in an IUE low-dispersion spectrum covers several pixels in the spatial and spectral directions owing to the finite resolutions of the telescope, spectrograph, and camera. A measurement of the line flux effectively averages over those many pixels and, thus, can have a different S/N ratio (hopefully larger) than that of, say, the peak pixel itself.

8.1 Model of the Spectral Extraction

Consider the following model for the extracted line flux. Assume that the stellar emission line has a two-dimensional profile specified by independent cross sections in the spatial and spectral directions, and that the stellar continuum has a cross section of similar width in the spatial direction but is uniform in the dispersion direction. Imagine an \(\mathcal{N} \times \mathcal{M}\) pixel\(^2\) area centered on the peak pixel. The total emission-line signal is

\[ f_{L} = \sum_{x,y} \epsilon_{x,y} DN_{L} = \Gamma_{x} \Gamma_{y} \times DN_{L}, \]

where \(x = 1, \ldots, \mathcal{N}\) refers to the dispersion direction; \(y = 1, \ldots, \mathcal{M}\) refers to the spatial direction, the \(\epsilon\)'s are the cross-section profile factors normalized to unity at the line peak pixel, the \(\Gamma\)'s are the sums of the respective \(\epsilon\)'s, and \(DN_{L}\) is the net DN at the line peak.

The total noise of the line-flux measurement, \(\sigma_{L}\), is the square root of the quadratic sum of the noise contributions from the \(\mathcal{N} \times \mathcal{M}\) (assumed) independent pixels,

\[ \sigma_{L} = \left( \sum_{x,y} \sigma_{x,y}^{2} \right)^{1/2}, \]

where

\[ \sigma_{x,y} = \alpha \times (\epsilon_{x,y} DN_{L} + \epsilon_{x,0} DN_{C} + BKG)^{1/2}. \]

8.2 Optimum Unweighted-Slit Extraction of SWP-LO's

The above case with \(\mathcal{N} = \mathcal{M} = 9\) corresponds to the standard (IUE Spectral Image Processing System) point-source scheme, but with a 13-point unweighted extraction window (1 extraction point = \(\sqrt{2}/2\) pixels) instead of the usual 18. If one assumes a symmetric Gaussian point-spread-function of 2.9 pixels FWHM (an average of the spatial/spectral profiles reported by Turnrose and Thompson (1984)), one obtains \(\Gamma_{x} = \Gamma_{y} \approx 3.1\). Figure 3 depicts schematically that realization of the spectral extraction. Using the cited parameters, one obtains

\[ S/N \approx \alpha^{-1} \times \frac{3.1 DN_{L}^{1/2}}{1 + 2.9 DN_{C}/DN_{L} + 8.5 BKG/\text{DN}_{L}}^{1/2}. \]

All else being equal, the scale factor \(\alpha\) is the critical quantity for determining the S/N of the line-flux measurement.

If the continuum is negligible equation (9) predicts that the S/N in the measured emission-line flux is \(\approx \alpha^{-1} \times DN_{L}^{1/2}\), for \(DN_{L} \approx BKG\), or about nine at C IV for a net line flux of 50 DN and \(\alpha = \alpha_{\text{eff}}\). The maximum attainable S/N at C IV in a single observation is \(\approx 57\) for a very short exposure of a very bright emission-line source where the peak DN in the line is at the full level (205 DN), the maximum for linear performance: Coleman and Snijders
The quantitative improvement in S/N expected from a "Gaussian extraction" over the unweighted 13-point slit is about 30% for $DN_L = BKG$. The improvement is negligible when $DN_L \gg BKG$ (because there is essentially no contribution to the noise from the background in the first place) and it reaches a maximum of about 40% for the case of a faint emission line on a high background.

Suppression of the background pixels is not the only advantage of the optimum weighted-slit extraction techniques. They also can provide for straightforward mitigation of cosmic-ray hits, for example. However, the increased S/N alone would be sufficient justification to consider the optimum techniques as a reasonable discussion model for predicting S/N levels in SWP low-dispersion spectra.

8.4 Application to $CIV \lambda 1549$

All of the accumulated counts (e.g., in eq. (8)) depend on the exposure time, $t_{e x p}$. One can derive an analytical relationship between the exposure time and the S/N ratio in the measured line flux, up to a maximum $t_{e x p}$ where the peak intensity in the line exceeds 205 DN. Beyond the full level the output counts increase more slowly than linearly with exposure time while the off-source background continues to increase inexorably in proportion to it: Dynamic range is compromised as well as S/N.

The accumulated DN due to process i is $DN_i = R_i \times t_{e x p}$, where $t_{e x p}$ is the exposure time (in minutes) and the rate coefficient $R_i$ is in DN m$^{-1}$.

The background fogging at $CIV \lambda 1549$ is:

$$R_{BKG} = 0.10 + 0.08 \times 10^{(FPM^{-1})} ,$$

where the first term refers to dark emission and afterglow and the second to cosmic radiation (for a Fields and Particle Monitor (FPM) reading in volts). The coefficients derive from, respectively, deep sky-background exposures taken exclusively during low-radiation time (see Table 1) and short exposures of bright sources taken under a range of particle radiation levels during NASA second shifts.

The (peak) fogging rate due to a $CIV$ emission source can be inferred by comparing the net DN levels in short exposures of a bright source like $\alpha$ Aur against the calibrated line fluxes in the extracted spectra

$$R_L = 0.09 \times f_{CIV} \times 10^{-12} ,$$

where $f_{CIV}$ is the integrated line strength in units of $10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ at Earth, and the measured linewidth is 5.8 Å FWHM (slightly larger than the instrumental value due to the 3 Å doublet separation). For convenience the relation can be rewritten in terms of a $CIV$-to-visual index, $f_{CIV} = f_{CIV}/f_V$, as follows:

$$R_L \approx 0.31 \times f_{CIV} \times 10^{-1.5} ,$$

where $V$ is the visual magnitude and $f$ is in units of $10^{-4}$.
the monochromatic visual flux is, $f_v = 3.4 \times 10^{-9} \times 10^{-9/2.5} \text{ergs cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$.

One can infer a relationship for the continuum fogging rate by multiplying the line rate by the resolution element,

$$R_C = 0.5 \times f_C (10^{-13})$$

where $f_C$ is the monochromatic continuum flux in units of $10^{-13} \text{ergs cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$ at Earth. An examination of Bennett’s (1987) cool-star database suggested the following relationship between the $\lambda 1549$ continuum fogging rate and the stellar visual magnitude $V$ and $(B-V)$ color index:

$$R_C \approx 0.4 \times 10^{-(V/2.5)-3.4(B-V)-1}$$

The total fogging at the peak of the C iv line is:

$$\text{DN}_{\text{max}} = (R_{\text{iso}} + R_C + R_{\text{BKG}}) \times t_{\text{exp}} + 15$$

where the last term is the camera pedestal DN$_{p}$. The net emission-line signal for the peak pixel would be, of course, DN$_{l} = R_{l} \times t_{\text{exp}}$.

Incorporating these relationships into equation (10), one can construct exposure diagrams for C iv like those of Figure 4. The diagrams demonstrate the clear disadvantages of a detector system with limited dynamic range: A bright stellar continuum or a high background due to particle radiation sets a limit on the maximum S/N attainable in a single observation, regardless of the exposure time.

### 8.5 Confrontation with Real SWP-LO Exposures

It is one thing to derive an expression to predict S/N ratios in IUE spectra and another thing to believe it. In fact—unlike a flat-field image—it is not a simple matter to measure the S/N of an emission feature recorded in an IUE spectrum. Fortunately, a large collection of SWP low-dispersion pseudotrailed triple exposures of the bright sources $\alpha$ Aur and $\alpha$ CMi are available to test the S/N formula.

The spectra were acquired during a program to monitor the far-ultraviolet emissions of several chromospherically active F-type stars on rotational time scales (days to weeks; see Ayres 1990). The observations were conducted during NASA second shifts, which often experience elevated levels of charged-particle radiation. The associated Cerenkov fogging can significantly raise the background DN on which the spectrum sits, and thereby change from day to day the portion of the photometric linearization function that is applied to it. Any subtle errors in the linearization potentially could produce an apparent variability of the line emission, even if the source itself was constant.

Thus, for each observation of the monitoring campaign an artificial background was introduced by means of a short tungsten lamp exposure to compensate for day-to-day differences in the particle-radiation levels. The TFL was maximum ($3.3 s = 60$ DN) when the particle fogging was negligible (FPM $\approx 1.0$ V) and decreased inversely with the radiation reading up to FPM $= 2.8$ V, at which point the particle background alone was equivalent to that produced by the maximum lamp exposure.

The on-source exposure time (3" 20′ for each subimage) was designed to yield a peak DN of $= 200 - 220$ for the C iv line of $\alpha$ Aur and the $\lambda 1216$ La emission of $\alpha$ CMi. The triple exposures were extracted from the spatially resolved files using custom software that, however, is traceable to standard (IUE Data Analysis Facility) procedures and calibration tables. In particular, a 22-point ($= 16$ pixels $= 24′$) unweighted extraction slit was utilized to encompass the effective spatial extent of the pseudotrailed image perpendicular to the dispersion line. The
far-ultraviolet time series of $\alpha$ Aur and $\alpha$ CMi represent a collection of homogeneous spectra acquired and processed in a very uniform manner.

Equation (8) applies to the partially blended triple exposures as follows: a $9 \times 16$ pixel “footprint” in raw-image space, a flat cross-section profile with Gaussian edges in the spatial direction (yielding $\Gamma_\sigma \approx 10.1$), and the 2.9-pixel FWHM response in the spectral direction (same $\Gamma_\sigma$ as for point-source example). The optimum extraction profile for the pseudotrailed image is the unweighted slit because the spatial cross section of the widened spectrum is nearly rectangular. The typical DN contributions to the C IV feature of $\alpha$ Aur are: BKG = 55 (set by the radiation compensation), $DN_L = 115$, and $DN_C = 35$ (mostly stellar photospheric emission, but some scattered light). The corresponding values for the $\lambda\alpha$ emission of $\alpha$ CMi are: BKG = 35, $DN_L = 140$, and $DN_C = 20$ (dominated by scattered light). With these parameters, and $\alpha \approx \alpha_{\text{max}}$, because the spectra were processed with the prevailing IUESIPS software, equation (8) predicts $S/N \approx 27$ for both of the measured line fluxes. By way of comparison, a single exposure with the same DN levels extracted by a Gaussian-weighted slot would yield $S/N \approx 16$. Thus, the unweightex extraction of the triple exposure is consistent with the V3 improvement expected from the coaddition of three independent single exposures, and the pseudotrailling saves substantially on camera operations overhead as well.

How do these predictions compare with reality? Figure 5 illustrates the C IV fluxes of $\alpha$ Aur and the $\lambda\alpha$ fluxes of $\alpha$ CMi recorded during the monitoring campaign. Also illustrated are broad-band largely photospheric continuum fluxes measured in the same spectrum to serve as a “control” for possible systematic errors that might produce an artificial variability from one image to the next. For example, pointing errors could cause “clipping” of one or both of the outer two images at the edges of the large aperture. The rms variances of the $\alpha$ Aur and $\alpha$ CMi fluxes are 5.3% and 3.6%, respectively, consistently with the predicted S/N ratios, particularly since a modest amount of stochastic source variability might be present in the fluxes of $\alpha$ Aur (but not in those of $\alpha$ CMi: see Ayres 1990).

Incidentally, the error bars on the line fluxes in Figure 5 were determined from a general formula given by Landman, Roussel-Dupré, and Tanigawa (1982). The typical flux uncertainties estimated in that way — 2.0% for $\alpha$ Aur and 2.8% for $\alpha$ CMi — are smaller than predicted by the S/N relation. However, the authors’ prescriptions assume a constant additive noise source, and the application to IUE spectra, with the apparent square-root behavior of noise, is somewhat inappropriate. On the one hand, the Landman, Roussel-Dupré, and Tanigawa algorithm should be reasonably valid for a weak emission line on a strong background (or stellar continuum), because the

Fig. 5—Observed C IV $\lambda 1549$ emission of $\alpha$ Aur and $\lambda 1216$ emission of $\alpha$ CMi over a one-month period in early 1986. The fluxes were extracted from SWP-LO triple exposures taken with uniform backgrounds (thanks to a radiation compensation scheme). Also included are broad-band continuum intensities in three ($\alpha$ Aur) or two ($\alpha$ CMi) 50 A–100 A windows recorded in the same spectra. The fluxes are displayed relative to the mean value over the period of observation. The variances of each set of line fluxes are comparable to the noise levels predicted on the basis of an analysis of mercury lamp flat fields and provide some confidence in the reality of the proposed S/N formula. (The two stars, particularly $\alpha$ CMi, were tolerably stable in their chromospheric emissions over that period so that the apparent variances should provide a reliable estimate of the random noise component.)

$\sigma_{\text{DN}}$ at the bottom of the line will be nearly the same as at the top. On the other hand, $\sigma_{\text{DN}}$ in the high-contrast C IV emission of $\alpha$ Aur decreases by about 40% from the line peak to the line base (at the continuum level). In the latter situation it is conceivable that the authors’ formula somewhat underestimates the true uncertainty in the line flux.

8.6 How Faint Can the IUE Be Pushed?

One of the important practical questions one might ask of the present work is: “What is the minimum detectable C IV flux in an IUE low-dispersion spectrum?” The faint limit of the IUE clearly will be attained for an object that has virtually no continuum emission at $\lambda 1549$.

One would conduct a deep SWP-LO exposure exclusively during low-radiation time, possibly stringing together more than two such shifts by holding the SWP camera in standby mode during an intervening high-radiation period. Exposures as long as 1500 minutes (25 h) have been taken using that strategy (Elgarøy et al. 1988). If the only sources of background are camera dark emission and afterglow, one can apply equation (10) with $DN_L/\Delta L = 0$, BKG = 0.11 $t_{\exp}$, and $DN_C = 0.09 f_{C,N} t_{\exp}$, where $f_{C,N}$ is the limiting integrated C IV flux in units of $10^{-13}$. For a given S/N ratio and exposure time, equation (10) yields a quadratic equation in $f_{C,N}$ which can be solved for the limiting flux. Figure 6 depicts $f_{C,N}$ as a function of
exposure time for three S/N ratios. For a definitive 5σ detection in the longest possible exposure, one can reach only as faint as a few \( \times 10^{-14} \text{ ergs cm}^{-2} \text{s}^{-1} \) at C IV, if \( \alpha = \alpha_{\text{eff}} \). The limiting flux will be higher, of course, if circumstances prevent at least partial degranulation of the processed spectra.

The preceding arguments pertain to the case of an isolated, unresolved emission feature. The faint limits for a broad-band featureless continuum could be much smaller: Averaging in the dispersion direction should depress the limiting flux approximately in proportion to the square root of the number of spectral resolution elements encompassed by the measurement.

9. Summary and Concluding Remarks

Evaluations of individual mercury lamp flat-field images taken with the SWP camera of the IUE reveal a Poisson-like square-root dependence of the random noise on the output signal. That dependence also is seen in photometrically corrected tungsten lamp and sky-background frames. However, the absolute noise levels are well beyond the realm of photon-noise limited performance suggested by the Camera User’s Guide and direct intercomparisons of sets of similarly exposed flat fields. The exaggerated noise in production-processed images appears to derive from incomplete compensation for the pixel-to-pixel granularity, a “fixed pattern” of the camera system. Consequently, the S/N of a point-source emission line recorded at the instrumental resolution and processed with the prevailing software cannot exceed about \( f_{1}/\sigma_{L} \approx 30 \), under the best of circumstances (which rarely, if at all, are attained in practice). More typically, the maximum S/N in the line-flux measurement is \( \approx 15 \). These limits could be improved in principle by more than a factor of two with a better compensation for the granularity.

The maximum attainable S/N in the line-flux measurement is further diminished by the presence of a stellar continuum, which both contributes noise and eats into the available dynamic range, and by variable camera backgrounds (like that induced by cosmic particle radiation) which have much the same deleterious effect as the source continuum. Pseudotrailing in the large aperture helps somewhat for bright sources, although the major benefit is in observing efficiency.

In the IUE lore it is often remarked that one long exposure is better than two shorter ones, owing to “read noise”. That adage certainly would be true if a large additive source were present in the SWP noise budget but is not true if the dominant noise source is multiplicative, as appears to be the case.

Despite the shortcomings of its ground software, the IUE has been very well suited for a wide variety of investigations, as the wealth of spectral information accumulated over the past 12 years attests (see Exploring the Universe with the IUE Satellite, edited by Y. Kondo). Even with the reality of HUBBLE, and the prospect of EUVE, LYMAN, and other state-of-the-art ultraviolet space observatories, the IUE still can play a valuable role in the present decade (see, e.g., Macchetto and Henry 1987), a period of paradigm-perestroika that promises to be every bit as revolutionary as the early years of the IUE mission.

I thank Mr. R. B. Burton for deriving the slope of the \( f_{1550}/(B-V) \) relation from Bennett’s cool-star database. I also have benefited from many conversations with the IUE Resident Astronomers and with other participants on the Final Archive Definition Committee. This work was supported by NASA grants NAG5-199 and NAG5-1215.

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