A Few Comments on Detectors

Charles L. Joseph
Princeton University Observatory

The IUE Project is about to spend a great deal of money and effort to reprocess the entire archive of data collected over the past 10 years. One question that readily comes to mind is: how can we be sure that the algorithm that we choose will be suitable for all of the data? I can easily envisage algorithms that would improve the data quality for say 3/4 of the images, but would be ineffective (or even do just the opposite) for the remaining 1/4 of the images. Further, the images that are in the most need of the signal-to-noise (S/N) enhancement are likely to be the very images for which typical algorithms are least effective.

Our understanding of the physical processes, leading to the formation of an image, has to be sufficiently complete in order to insure the selection of an adequate algorithm. Judging from the amount of information presented at this workshop and in the IUE Newsletters, a great deal of effort has already gone into studying the data quality. However, none of these studies appears to be comprehensive in nature and many are not quantitative enough to provide detailed information of the noise properties of the detector. In addition, the IUE SEC-vidicon, because its pixels are not linearly independent of each other and because it has a nonlinear response to photons, is a particularly difficult detector to evaluate and especially to develop algorithms to remove all of the detector response.

New detectors (developed after the launch of the IUE) are simpler in many ways than are vidicons. In order to illustrate some of the concerns raise above as well as to set the stage for a discussion of the physical processes operating inside the IUE detectors, these detector systems will be examined first.

In most detectors (e.g. microchannel type, CCD's, reticons), each pixel is (to a high level of accuracy) linearly independent of the others. This feature, which is *not* applicable to the IUE SEC-vidicons, means that each pixel can be treated as an independent photometer. In addition, the pixels usually have a linear response to photons over a large range of exposure levels; that is, the sensitivity is independent of the total accumulated exposure. Under these circumstances, each photometer (pixel) has some constant efficiency with which it converts photons to a measurable electrical signal and the sensitivity of one pixel differs from that of another merely by a *multiplicative* factor. These multiplicative factors can be measured by uniformly flooding the detector with light. Then, the pixel-to-pixel response (often referred to as fixed-pattern noise) can be removed by weighting the pixel-to-pixel values in a raw image by the inverse values determined from the uniform illumination. This process is often called rectification or flat-fielding as well as "using a template star".

Each independent photometer (pixel) also produces a signal in the absence of incident photons. Detectors that are sensitive to infrared and the long wavelength end of the optical spectrum generally have larger dark signals than do detectors that are sensitive only to blue and ultraviolet photons. Note that if the detector has a conversion stage like the IUE, which first converts the UV photons to optical ones, the detector normally behaves like the long-wavelength detector as far as the dark levels are concerned. In addition, detectors in a space environment are susceptible to backgrounds, whether they be charged particles bombarding the detector or stray light such as geocoronal lyman-alpha entering the aperture of the camera. The pixel-to-pixel response to the background is frequently distinctly different from the pixel-to-pixel dark levels as well as from the fixed pattern noise, requiring each to be measured independently and removed separately in order to achieve the highest data quality.

An algebraic formula can be used to remove the detector response, if the detector has good temporal stability as well as the two characteristics listed above. The formula is usually of the form:

$$I_i=(R_i-D_i-B_i)/(F_i/<F>) \qquad (1)$$

where I_i, R_i, D_i, B_i, and F_i are the intrinsic level of the image (or spectra) produced by the astronomical source, the raw (uncorrected) image, the dark, the background, and the flat-field (TFLOOD) response of the i'th pixel, respectively. $<F>$ is the mean flat-field response (i.e. the sum of the F_i's divided by the number of pixels). Hence, the uncertainties in most detectors arise from additive or multiplicative processes since the only mathematical operations are subtraction and division. See, for example, Bevington (1969) for the mathematical formulae for computing the propagation of errors from additive or multiplicative numbers, having uncertainties.

As already stated, the best method to achieve the highest quality data is to measure and to remove all of these parameters separately for each pixel. Sometimes, however, instrumental constraints do not readily permit complete removal of the detector response, thus, reducing the intrinsic S/N ratio of the final data. The situation can be even worse if an inappropriate correction algorithm is used because additive noise sources have been confused with multiplicative ones. Table 1 shows a hypothetical example in which this confusion leads to the application of an incorrect algorithm, occasionally degrading the data quality.

The table depicts the individual relative responses to photons, to the background, and to the dark signal of two pixels. The random noise component will be ignored throughout this paper because we are only interested in isolating and removing the systematic pixel-to-pixel differences in the detector response. All of the values are weighted to a mean of unity. Two environments are compared: Case A) the background is insignificant and only a stellar flux plus a small dark level are present, and Case B) the same as Case A, except with the presence of a strong background. The rows labeled: "Total Relative Response" are the relative net values expected after subtracting a mean dark level and background, but leaving in the pixel-to-pixel difference from all three sources. The (Pixel I)/(Pixel J) sensitivity ratios are given at the far right. Thus, it can be seen that Pixel I has 22% more sensitivity to photons than does Pixel J, but has 18% less dark signal.

In this hypothetical example, it would be very easy for an investigator to infer from the examination of a number of Case A-type exposures that pixel I is systematically higher than pixel J and therefore, must be about 1.17 times more sensitive than pixel J. Note: 1.22 is the real sensitivity ratio for incident photons. Furthermore, that same researcher could take any other Case A-type exposure and by dividing the flux for pixel I by 1.08 and the flux for pixel J by 0.92 could improve the apparent S/N ratio between these two pixels. However, not all of the detector response is removed for Case A images and if the investigator tries to use these same divisors on a Case B-type exposure, he will accentuate (not decrease) the pixel-to-pixel difference. The Case B/Case A numbers, depicted at the bottom of the table, demonstrates that using Case A images as a template for Case B images causes the I/J ratio to be 0.80 rather than 0.94. Ideally, the ratio should approach 1.00 asymptotically as the algorithm becomes perfect.

Again, the IUE detectors do not have pixels that are linearly independent nor do they have pixels that have a linear response to exposure level. Hence, a simple algebraic formula is not feasible. Instead, the IUE Project uses an empirically determined mapping function (known as the Intensity Transfer Function or ITF) to transform charge accumulations into flux numbers. In principle, this mapping could remove all of the dark, background, and flat-field detector response. The current ITF, however, has been shown not to remove all of the detector response (e.g. Clarke 1981, York and Jura 1982, Leckrone and Adelman 1988). The problem now is to determine the nature of the residual detector response still remaining in the data or to produce a more comprehensive ITF, perhaps one that includes a pixel-by-pixel response to the dark and background levels.

All methods to maximize the S/N ratios in IUE data have pitfalls. A more comprehensive ITF, for example, is complicated by the fact that the pixels are not linearly independent of each other. Thus, a trailed spectra may require a separate ITF from the one used for nontrailed images in order to achieve the highest possible S/N ratio. It is quite likely that the only pixels truly represented by the current ITF are those near the center (perpendicular to the dispersion) of an echelle order because these are the only ones with neighboring pixels comparably exposed. The ITF for a pixel is determine currently from images where the flux on a pixel is comparable to that of its adjacent neighbors. This ITF should differ from an ITF where the neighboring pixels were not comparably exposed. In addition, the ITF for an individual pixel may be altered by the presence of a large background flux. Two sets of ITF's might be required, one for low and one for high backgrounds. Both GEX and Optimal Spectral Extraction Routine probably owe some of their apparent success in improving the S/N ratio to the suppression of information contained in pixels not correctly represented by the current ITF. Would these two routines improve the data quality as much if a better ITF (or set of ITF's) were used?

Likewise, algorithms, which attempt to compensate for the inadequacies of the ITF, may be plagued by difficulties similar to those demonstrated in table 1. It is often difficult to separate conclusively multiplicative from additive residuals when the departures are modest in size. In addition, these routines have the basic problem of attempting to apply a simple formula, analogous to equation 1, to a set data that have a strong nonlinear behavior, which is also dependent upon the type of data being analyzed. Do the inadequacies of the ITF preferentially leave behind residuals that are extremely nonlinear? Do the pixel-to-pixel residuals differ multiplicatively, additively, or have both components? How universal is any algorithm? Will an algorithm work for images with high backgrounds as well as for spectra with low backgrounds? All of the well developed algorithms have been extensively applied only to bright sources where the background is insignificant.

Nevertheless, we should be encouraged by the results of various algorithms. Significant S/N improvements over those normally obtained with a single IUE image often have been realized by using trailed spectra as a template for removing the "fixed pattern" from a nontrailed image (Welty *et al.* 1986). This result probably indicates that the values in one pixel are not influenced too severely by values in its neighbors. The work by numerous authors suggest that the IUE has temporal stability (at least to some reasonable level), which is necessary to the success of any algorithm.

One particularly promising development has been the recent discovery that better pixel-to-pixel registration between the pixels in the images used to create the ITF and those from the raw images significantly enhances the signal-to-noise ratio (Nichols-Bohlin 1988). All of the most successful algorithms appear to be based on the principle of carefully registering pixels of a raw image to pixels of a calibrating spectrum. Hence, a better application of the current ITF may provide most (if not all) of the intrinsic improvement that can be accomplished with the various algorithms developed to date.

It should be noted that all of the current methods still fall short of the theoretically possible S/N ratios. Improving the data quality above the levels that can be obtained presently will be increasingly difficult and will probably require customized processing to meet individual types of images. Considering the size of the task and the timescale for implementing it, I think the IUE Project should only consider reprocessing with improved registration between the images used to create the ITF and the raw images. Other processing schemes have not yet been demonstrated to be universal and may do a disservice to reasonable percentage of the images. The IUE Project, however, should consider the feasibility of creating various catalogues, for example, of template stars or of template backgrounds so that future investigators could experiment with various reduction concepts with a minimal amount of effort.

References:

Bevington, P. R., *Data Reduction and Error Analysis for the Physical Sciences,* (New York: McGraw-Hill).

Clark, J. T. 1981, NASA Newsletter, No. 14, 149.

Lechrone, D. S., and Adelman, S. J. 1988, preprint #88-16, Goddard Space Flight Center.

Nichols-Bohlin, J..1988, NASA Newsletter, No. 34, 57.

York, D. G., and Jura, M. 1982, Ap. J., 254, 88.

Welty, D. E., York, D. G., and Hobbs, L. M. 1986, P.A.S.P., 98, 857.

Relative Response for Pixels I and J

Source of Signal	Pixel I	Pixel J	I/J
Rel. Resp. to Photons:	1.10	0.90	1.22
Rel. Resp. to BKG:	0.85	1.15	0.74
Rel. Resp. to Dark:	0.90	1.10	0.82
Case A			
Photons are 5/6 of total signal:	0.92	0.75	
BKG is neglegable:			
Dark is 1/6 of total signal:	0.15	0.18	
Total Relative Response: (R - <B> - <D>)	1.08	0.92	1.17
Case B			
Photons are 1/2 of total signal:	0.55	0.45	
BKG is 1/3 of total signal:	0.27	0.40	
Dark is 1/6 of total signal:	0.15	0.18	
Total Relative Response: (R - <B> - <D>)	0.97	1.03	0.94
Case B/Case A:	0.90	1.12	0.80