IUE'S LEGACY FOR THE FUTURE: THE FINAL ARCHIVE AND GOALS FOR ITS IMPLEMENTATION

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ABSTRACT

Since the final IUE archive will contain enormously valuable information for future astronomers, it is important to plan now how to create a useful archive of the highest quality data. We describe briefly some requirements for this archive, and describe how the signal/noise ratio in photometrically corrected images can be enhanced considerably by cross-correlating the fixed pattern in a data image with that in a suitable flat-field image. From these cross-correlations it is feasible to derive an accurate geometrical correction to apply to the data image before applying the Intensity Transfer Functions (ITFs). At present the standard IUE processing software does not generate a sufficiently accurate geometric correction so that typical spatial errors of 1-2 pixels conspire with the large fixed pattern in raw images to produce significant "misregistration noise". Tests on flat-field images demonstrate that an explicit geometric correction procedure can avoid most of the misregistration noise and can thereby improve the S/N ratio of IUE data by factors of 1.5 to 2.4.

Keywords: IUE Data Processing, IUE Data Archives, Signal/Noise Optimization, Misregistration Noise, Spectral Extraction.

1. Introduction

At some future time the IUE satellite will obtain its last astronomical spectrum, but the scientific accomplishments of the IUE should then be far from complete. While we hope that the end of IUE operations will be in the distant future, it is prudent to prepare now for the long era when astronomers will use the archives to study the historical record of interesting sources, for multiwavelength studies, and to plan future observations.

After the completion of IUE operations, the users of IUE should leave for future generations of astronomers the most useful and accessible archive of the highest quality astronomical spectra that can be created. We emphasize the words useful, accessible, highest quality, and create.

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There are two important reasons why we should do so. First, the reputation acquired for a job well done in a cost-effective way is a powerful argument that the ultraviolet astronomy community can be entrusted with future missions like LYMAN. Second, astrophysics has become problem-oriented rather than wavelength-oriented, so that ultraviolet spectroscopy is but one tool that should be used in conjunction with other observational and theoretical tools to understand astrophysical phenomena. Multiwavelength astrophysicists of the future cannot be expected to learn the intricacies of many instruments in order to acquire high quality data across the electromagnetic spectrum. On the contrary, if the archival data require complex reduction or considerable effort to be used, then the archive has been lost.

Consider the following scenario that will likely occur often after the completion of IUE operations. The detection of a new phenomenon indicated by some ultraviolet spectral feature will generate a search of the IUE archives for "historical" spectra of the same object or brighter members of the class. If the IUE archival data are very noisy or contain spectral features that are artifacts rather than real features, then the literature will become glutted with theoretical "explanation" of such noise or artifacts. Thus, the preparation of the highest quality archives may be among the most important scientific tasks remaining for IUE.

One should harbor no illusions that the task is small. Nearly 70,000 images have already been obtained and the list is growing at the rate of 7000 per year. Two years may be required just to prepare for the reprocessing and 2-3 additional years to accomplish the task. Realistically, reprocessing of the data will be done only once, and therefore we must do it right the first time. So, what needs to be done?

2. Requirements for the Final IUE Data Archive

1. Completeness. Clearly all of the IUE images, including both the NASA and VILSPA images, should reside in the archives.
2. **Documentation.** The documentation accompanying the archive should be complete, with a users' guide understandable to astronomers who are unfamiliar with IUE and its data.

3. **Accuracy.** The information in the image headers and elsewhere should be verified and corrected where necessary.

4. **Uniformity.** One processing procedure should be applied to all images, so that the whole data set can be intercompared and understood. This is especially important for statistical studies of large samples of targets.

5. **Modern formats.** The data should be transcribed into the generally accepted FITS format to ensure portability to modern machines and compatibility with IRAF and MIDAS.

6. **Modern media.** The whole data set should be available on an few optical disks, but also on floppy disks for astronomers who do not have access to the still expensive optical disk technology.

7. **Photometric precision and accuracy.** The most recent and accurate ITFs (intensity transfer functions) and absolute flux calibrations and their known time variations for each camera should be applied in a consistent manner.

8. **Signal/Noise optimization.** Recent work, as described later in this paper, indicates that substantial improvements can be made in the signal/noise (S/N) of IUE spectra by avoiding misregistration noise, extracting the spectra by new methods, and perhaps also by removing electronic noise. We use the term "misregistration noise" to describe the effect of insufficiently accurate mapping of the raw image onto the two dimensional grid of ITFs that differ significantly from pixel to pixel. Thus in the standard IUESIPS processing software, the ITFs for the wrong pixels are often used to photometrically correct the raw images. Since techniques for avoiding misregistration noise and optimizing the S/N at the spectral extraction stage have been demonstrated on test spectra, it is important to devise and test procedures that may be used to reprocess the whole IUE data set in a batch processing mode.

9. **Files to be included.** The final archive should include for each exposure: the raw image, the geometrically and photometrically-corrected image, and one or more spectral files in which the spectrum is extracted in different ways. For example, a simple boxcar weighting function in the direction perpendicular to the dispersion could be used when the most accurate photometry is needed and a Gaussian or optimal extraction procedure used when the highest S/N is desired.

10. **Reasonable promptness.** The reprocessing should begin only after we understand how to do the job well, rather than be driven by an artificial time constraint. This means that a systematic development effort should be funded now. Just as NASA/ESA and the SERC have supported all aspects of the IUE program up to now, they would support the development process and the production of the final data archives.

3. **Signal/Noise Optimization.**

While the sensitivity of the IUE spectrographs and cameras cannot be increased, the noise can be reduced significantly. This is especially important for weakly-exposed spectra and studies of weak absorption or emission lines superimposed on well-exposed spectra. Processed IUE images and spectra provided to the observer and now placed in the archives contain several types of noise (cf. Ref. 1). These include the radiation-induced background due to Cerenkov photons in the camera faceplate, phosphorescence in the UV converter from previous exposures and the preparation cycle floodlamp illumination, incompletely erased previous images, electronic noise (i.e. microphonics), readout noise, radioactive decay events and cosmic ray hits in the UV converter, true photon statistics, and misregistration noise. Discrete noise spots on the IUE images can be readily identified and in principle removed in the pipeline processing software (IUESIPS) or by the astronomer using the extracted spectrum or the photometrically-corrected image. There is no need to go back to the raw image. In order to reduce the misalignment noise, however, one should reprocess the raw image, which involves considerably more expertise than can be expected of future IUE archive users. Thus the whole archive must be reprocessed to correct for this form of noise.

The first step in the photometric calibration of IUE raw images is the creation of a two-dimensional grid of ITFs that convert the raw signal data numbers (DN) to linearized flux numbers (FN) on a pixel-by-pixel basis for the whole IUE image. These ITFs are constructed using flat-field images illuminated by the on-board UV-floodlamp in a sequence of exposure levels. The IUE pixels are not physical, as in a CCD, but rather are determined from the time at which the SEC Vidicon electron beam scans the photocathode target.

The electronic nature of the IUE raw image pixels raises at least two important issues. First, the mapping of the optical image at the UV converter head to the electronic image on SEC Vidicon target is not stable due to the variable electric, magnetic, and thermal environments in the UV converter and SEC Vidicon. Second, the electron read beam may not always land at the same place on the target at the same time due to different space charge distributions (beam pulling) and other effects. Thus the correspondence of the raw image to the optical output image of the spectrograph changes with time, and a geometrical mapping of the raw image to the geometry at the input of the UV converter is required.

There are several possible approaches for implementing this geometrical correction. One approach is to use the reseaux, which are small dark dots about 2-3 pixels square and arranged in a regular grid with 5 pixels separation, located on the head of each UV converter. The reseaux are identified as dark spots on flat-field images and are used to coalign the individual flat-field images used to construct the ITF files. An important characteristic of SEC Vidicons is an inherent graininess in photometric sensitivity across the potassium chloride target which is scanned to produce a raw image. This graininess appears to be very long lived, perhaps for the full life of the Vidicons, but it may vary
somewhat with time. This graininess is responsible for the large pixel-to-pixel variations in DN values seen in the raw flat-field and astronomical source images that is commonly called the "fixed pattern".

If SEC Vidicons were like CCDs, which have fixed physical pixels, then the fixed pattern in the raw images could be removed to high precision by a simple division by a flat-field frame. Implementation of this procedure for IUE images is frustrated by time-dependent geometrical distortions between the optical image and the raw image. These distortions are commonly 1-2 pixels in magnitude and are not simple geometric translations. When the geometrical corrections are not sufficiently precise, then the ITFs for the wrong pixels are applied. Since the ITFs vary by 10-15% from pixel to pixel, the effect of an imprecise geometrical correction is a photometrically-corrected image with enhanced noise on the scale of one pixel. We refer to this noise as "misregistration noise" which can best be suppressed by an accurate geometrical correction.

4. Tests of Signal/Noise Optimization on Flat-Field Images

As part of the effort to study the misregistration noise in IUE data, a preliminary analysis for the SWP camera has been performed. Six flat-field SWP UV-flood images were selected for the current analysis. Three of the images were taken at a 60% exposure level and three at a 120% exposure level. The images chosen were acquired over the eight year period 1978-1986, in order to identify any time-dependency in the suitability of the two available Intensity Transfer Functions (ITFs) for this camera. The analysis has been limited to the SWP camera at this point, but will be extended to the two long-wavelength cameras in the near future.

4.1 Procedure

Each test image was photometrically corrected in two ways:

1. Explicit geometric correction with found reseau positions. In this method the reseau marks on the flat-field test image are located and their positions used to geometrically correct the test image. The ITFs are then directly applied to the geometrically-corrected test image to produce a photometrically-corrected image.

2. Implicit geometric correction using mean reseau positions. This method is equivalent to the procedure used by IUESIPS in the normal processing of data images. Since the reauxes are not easily located on data images, this procedure uses a set of mean reseau positions which have been positionally extrapolated using time and temperature dependencies. Instead of geometrically correcting the data images, the ITF array is mapped into the raw data image space, using these mean reseau positions, to photometrically correct the data image.

One caveat must be noted. In the first method, both the test and the ITF images are smoothed once during the geometric correction procedure. In the second method, the ITF images are smoothed twice (once during geometric correction and once when mapping to the raw test image space) but the test image is never smoothed. These two smoothing procedures are not equivalent and the first method indeed produces more smoothing (and thus a higher signal-to-noise ratio) than the second. This smoothing accounts for 10-50% of the improved S/N reported here.

4.2 Statistics

In order to assess the quantitative impact of the two methods of photometric correction described above, each resulting test image was divided into four mutually-exclusive square areas. Each area is the largest possible square lying entirely inside the target ring, with one corner at the center of the image. The areas are numbered 1,2,3 and 4 for the upper left, upper right, lower left and lower right portions of the image. Within each of these numbered areas, 12x12 pixel boxes were used to determine a mean flux, standard deviation of the flux, and resulting signal/noise (S/N) ratio for the large numbered area.

4.3 Results

Fig. 1 shows plots of the S/N ratio for each of the four large areas vs. time (year of image acquisition). The asterisks represent explicit geometric corrections using the found reseau positions and new ITFs, the plus marks represent explicit geometric corrections using found reseau positions and the old ITFs; the "x" marks represent the implicit geometric corrections using mean reseau positions and the new ITFs, and finally, the diamonds represent the implicit geometric corrections using mean reseau positions and the old ITFs. Only the results for the 60% level exposures have been reproduced here; the results for the 120% level are basically similar to those presented here and contain no additional information. The plots have been arranged in the same configuration as the areas on the image they represent.

It is immediately apparent that the explicit geometric correction using found reseau positions always yields a significantly higher S/N ratio (by factors of 1.4 to 2.5) than the normal production processing by IUESIPS. This result is true regardless of the year of image acquisition or ITF used. In fact, a major conclusion of this work is that the choice of which ITFs to use is much less important important than the proper alignment of the ITFs with the raw data image pixels. Clearly, improved alignment of the ITFs with the data images has great potential for improving the S/N ratio of IUE data.

Geometric correction, either explicit or implicit, using found reseau positions is not practical for normal production processing because data images usually have a background level that is too low for automated reseau location.

Linde and Dravins (Ref. 2) demonstrated that an accurate procedure for geometrically correcting the raw data image is to use the fixed pattern itself as a fiducial. They select subimages of 7-9 pixels located about 20 pixels apart and between the spectral orders (in high dispersion). Each subimage is then cross-correlated with a flat-field image (with similar DN values) used in creating the ITF array for that camera. The resultant grid of geometrical correction vectors is then smoothed using two-dimensional cubic splines to define a smooth vector field that is used to regrid the raw image onto the grid of ITFs before performing the
Fig. 1. Plots of S/N ratio for each of the four large areas in a flat-field image vs. time (year of image acquisition). The asterisks represent explicit geometric corrections using the found reseau positions and new ITFs, the plus marks represent explicit geometric corrections using found reseau positions and the old ITFs, the "x" marks represent the implicit geometric corrections using mean reseau positions and the new ITFs, and the diamonds represent the implicit geometric corrections using mean reseau positions and the old ITFs. The plots have been arranged in the same configuration as the areas on the image they represent.

photometric correction. The effect is to remove most of the fixed pattern in the interorder regions and also in the echelle order spectra. This procedure is illustrated in a video shown elsewhere at this meeting (Ref. 3).

A critical test of the geometrical precision required is shown in Scene J of the Linde-Dravins video where the geometrically corrected image is blinked against the IUESIPS-processed image and an image geometrically corrected using the Linde-Dravins method but then deliberately offset by 0.4 pixels in one direction before the photometric correction is applied. The effect of the 0.4 pixel offset is to produce obvious misregistration noise that is smaller in magnitude than what is produced by the IUESIPS processing, both before and after IUESIPS was changed from a crude explicit to an implicit geometric correction scheme in 1980-1982 (Ref. 1). Thus the accuracy of the geometric correction must be significantly better than 0.4 pixels, but further studies are needed to determine whether a precision of 0.2 pixels or even 0.1 pixels is required to remove the misregistration noise.

Welty, York and Hobbs (Ref. 4) and Welty and York (Ref. 5) have described an alternative method for reducing the misregistration noise that manipulates spectra extracted from the IUESIPS-processed images. They coaligned 15 spectra of the hot star Eta Lup to bring out the fixed pattern. The stellar continuum regions of this template were then divided into individual spectra of the target star Rho Oph after the fixed pattern of the target star and template spectra were coaligned. The effect was to reduce the noise level in individual spectra and to increase the S/N in coadded (and appropriately shifted) spectra by a factor of the square root of the number of images, as expected for spectra in which systematic contributions to the noise are small. The applicability of this technique remains to be determined, but the apparent need for a large number of different templates is an argument against its use for reprocessing the whole IUE data set.

5. Improvements in Spectral Extraction Procedures

Spectra are presently extracted in IUESIPS from photometrically-corrected images by running a numerical slit 1 pixel wide (dispersion direction) and 9 pixels high (perpendicular to the dispersion) for low dispersion and variable for high dispersion, along the spectral orders. This procedure, which is described in more detail by Harris and Sonneborn (Ref. 1) is relatively simple to implement and has high photometric precision, because essentially all of the light in the optical image lies within the extraction slit. However, this procedure weights those pixels centered along each order, where the image is brightest, equally with those pixels located well above and below the spectral orders, where
there is little light. Thus the extracted spectrum weights noisy pixels too much and the extracted spectrum does not have optimal S/N.

Two new extraction procedures have been developed to enhance the S/N by assigning higher weights to pixels with larger spectral flux. One approach is to employ a Gaussian weighting function to pixels located away from the center of the spectral orders with either the Gaussian width fixed (Ref. 2) or determined empirically (Ref. 6). The latter authors find that their procedure improves the S/N by a factor of 2 over IUESIPS for poorly exposed spectra.

Horne (Ref. 7) and Kinney and Rivolo (Ref. 8) describe a second approach, the so-called “optimal extraction algorithm”. This algorithm assumes that the spatial profile (the distribution of flux perpendicular to the dispersion) varies slowly with wavelength and determines its shape empirically while preserving positivity and enforcing photometric precision. The algorithm removes cosmic ray hits and other narrow blemishes with an iterative procedure and subtracts the background using a median filter. The authors state that the spectra of flux-standard stars should be extracted with the same procedure to obtain the highest photometric precision.

Determining which of the extraction procedures are best suited for batch processing of the heterogeneous IUE data set requires further study, but a sensible plan might be to include both the simple IUESIPS extraction and either a Gaussian or an optimal extraction procedure for the final IUE archival data.

6. For the Future

Since the task of reprocessing the whole IUE data set for the final archives is large, considerable planning and testing of different algorithms on a diverse sample of images is required. An important step in this process was the first Workshop on IUE Signal-to-Noise Improvement held at Goddard on 19-20 October 1987. Many of the papers presented at this workshop will appear in IUE NASA Newsletter #34. The Second Workshop will be held on 17-18 May 1988, also at Goddard with the goal of providing a tentative implementation plan and cost and time estimates for the reprocessing. We would welcome ideas from the IUE user community concerning how the final archives should be prepared.

References