An Improved Background Smoothing Technique for IUE Extracted Spectral Data

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1. INTRODUCTION

The background at the location of the spectral orders in IUE images is estimated from the response of the detector at positions adjacent to the spectral orders, rather than from dedicated background observations. Since the noise characteristics at the location of the background may be different from those at the location of each spectral order, a smooth representation of the background is subtracted from the gross spectrum in order to generate a net spectrum. This study is actually a belated response to an internal memo written in 1979 by Penston, in which he suggested the replacement of the triangular-filtered background (two mean filters applied successively) initially implemented in IUESIPS by a least squares fit to the background using a low order polynomial. In 1980 the project instead adopted use of a median filter (Turnrose, Harvel, and Bohlin 1979) followed by a triangular filter. The hope was that this combination of filters would "eliminate" bright spots, cosmic ray hits, and other narrow features as long as their widths are less than half the median filter window. Actually, random noise in the data serves to leave behind a residual signature of narrow bright spots, a result not anticipated by Turnrose *et al.* Grady *et al* 1989 have found that this approach results in the introduction of spurious features into the net spectrum whose width is of order of the filter window. Some of these features are caused by random noise in the off-order extracted backgrounds, whereas other features are attributable to cosmic rays in the background which do not affect the gross spectrum. As a result, an alternate approach to deriving a smooth representation to the background is clearly desirable.

2. CRITERIA FOR A SMOOTHED BACKGROUND

We have identified three criteria that can be applied to techniques for deriving a smooth representation of the off-order background. First, a smooth background should have the fewest local extrema and structure needed to repove features in the gross spectrum that cannot be ascribed either to the astronomical source or to instrumental characteristics, such as the echelle blaze function. In particular, a smooth background should not have structure on the same spatial scale as real spectral features, since the presence of such spectra will distort the net spectrum, making interpretation and analysis of the data difficult. This criterion relies on the availability of featureless astronomical spectra and is difficult to quantify. The second criterion supplements the first by requiring a background which minimizes a goodness of fit statistic, such as the reduced χ^2 or root-mean-square residual. The third constraint assumes that there may be several ways of deriving a smooth background which are approximately equally good. In this case, the lowest order or least heavily filtered version of the background should be used.

3. CHOICE OF FITTING TECHNIQUE

We have identified two distinct approaches to deriving a smooth representation of the background: filtering and fitting the data according to some least-squares criterion. As noted above, the choice of filters and filter widths for IUESIPS have caused the introduction of spurious features into ostensibly featureless net spectra. Filtering techniques in general, unless employing very sophisticated models for the appearance of the background, do not adequately reject cosmic ray hits, but instead smear the "flux" over a number of adjacent samples. Fitting techniques have an advantage here in easily rejecting spikes covering a small number of samples. As a result, the remainder of our discussion will focus on fitting techniques.

We have explored two classes of fitting technique: smoothing splines and least squares fitting using one or more functions. Smoothing splines are an extension of the more common spline interpolation technique which is typically used on datasets with comparatively widely spaced data points. In this technique, the spline functions are forced to pass within the 1σ error estimate at each datapoint, and to satisfy the usual continuity, and continuity of derivatives conditions. In a data set with many data points, such as a typical off-order background from IUE data, this technique can be used if representative data points are identified, and if some estimate of the 1σ errors can be provided. One way to do this would be to bin the background data over some interval and to use the mean and standard deviation in each interval as the representative point. Choice of the bin width and grid would, in some sense, be completely arbitrary. The results of the smoothing spline fits are, typically, very sensitive to the location of the representative data points. This sensitivity to the location of the representative points and the arbitrariness in selecting those points makes this technique not particularly suitable for production processing of large numbers of IUE spectra, although it would be suitable for interactive reduction of limited datasets, where the scientist can maintain more careful control over the selection of representative points.

The alternate approach of least-squares fitting of the data to some simple, low-order model is a technique which does not rely upon prior knowledge of the characteristics of the background data, except in selecting the appropriate model. In particular, we do not need to do any prior binning to be able to estimate the uncertainties in the data, which makes this kind of approach sufficiently automated for use in production image processing. A further advantage is that the technique is familiar to essentially all astronomers, making the handling of the IUE data less mysterious. We have explored two approaches to the fit model. One is to use a simple fixed model, such as a single, low-order polynomial of degree n. This approach can be quite satisfactory, provided that the shape of the backgrounds is the same for all orders of a particular dispersion mode and camera independent of the nature of source. If the shape of the background changes with illumination, or order number this approach can result in unsatisfactory fits to the background, and less than optimal net spectra.

An alternate approach is to use not one, but a set of related functions, such that an arbitrary background spectrum can be represented as the linear combination of the individual basis functions. If the basis functions are orthogonal, individual functions having a negligible component in the data set to be fitted will have negligibly small fit coefficients. The choice of model is then simplified to making sure that a sufficiently high number of basis functions are included to follow the relevant structure in the background data. This makes the choice of model less arbitrary than if only a single function is used, but still results in an algorithm which is robust, and very automated. We have chosen to use a set of low-order, Chebyshev polynomials as our basis functions, since these are mathematically equivalent to other representations, but are particularly easy to implement numerically. The Chebyshev polynomials are given by $T_0=1$, $T_1=x$, and $T_{n+1}(x)=2xT_n(x)-T_{n-1}(x)$ for $n\geq 1$. We have used the FORTRAN program LFIT from *Numerical Recipes* (Press *et al.* 1986) for the majority of our analysis.

4. NUMBER OF POLYNOMIALS NEEDED

a) Low Dispersion

Three to four optimally exposed calibration spectra were chosen for each camera to evaluate the number of polynomials needed to ensure an adequate fit to the inter-order background. Figure 1 shows the trend of rms residuals of the unsmoothed data with respect to Chebyshev polynomial fits containing orders T_0 through T_n, where n is the highest order polynomial in the fit. The horizontal line is the rms residual of the unsmoothed data with respect to the IUESIPS smoothed background. The different plot symbols correspond to different images. For each camera the test small aperture spectrum is represented by an X. No significant difference is seen in the trend of residual as a function of n as a function of the aperture. We find that the residuals decrease rapidly from $n=1$ to 5 and then decrease more slowly thereafter, asymptotically approaching the IUESIPS limit by $n\approx 15$. In accordance with our criteria for a smooth background, acceptable fits can be achieved using T_0 through T_6. Figure 2 shows representative fits using these polynomials for each camera. The noisy curve in the upper panel is the unsmoothed IUESIPS inter-order background. The wiggly curve is the filtered IUESIPS background. The smoothest curve is the fitted curve.

b) High Dispersion

We have made a similar evaluation of single orders in 4 high dispersion, optimally exposed spectra for each camera (3 large aperture, 1 small aperture), again using the inter-order background stored in the MEHI file. Figure 3 shows the trend of rms residuals as a function of highest order number, n, in the fit. As for the low dispersion case, the residuals decrease sharply for $n=2$-3, and are approximately constant for $n=4$-7. For higher n the residuals can decrease slightly to the IUESIPS limit. Inspection of net spectra for these high order fits shows that the spectral artifacts first noted by Grady *et al.* (1989) have reappeared. The optimal range for fitting is therefore $n=4$-7 for all three cameras. If minimizing computation time is important, $n=4$ produces adequate fits. If using the same number of polynomials for low and high dispersion is important, $n=6$ provides good fits.

5. RESPONSE OF THE FITTING ALGORITHM TO "PROBLEM" DATA

a) Weakly Exposed Data

Figure 5 shows the effect of changing from the IUESIPS filtered background to a Chebyshev polynomial fitted background for order 100 of LWP 7913, the spectrum used by Grady *et al.* (1989) to illustrate the background handling problems of the IUESIPS filter. The heavy curve is the net spectrum generated with the fitted background. The light curve is the IUESIPS net spectrum. The curve at the bottom of the figure is the unsmoothed difference spectrum shown to scale. Changing from the IUESIPS background filtering technique to the fitting technique introduces localized changes in the net spectrum as large as 10% near the sensitivity maximum, with the artifacts (spurious emission and absorption features) significantly reduced in the net spectrum generated with the fitted background. These changes cause the net spectrum to more closely approach the sinc^2 dependence on wavelength predicted for an echelle spectrograph. The remaining asymmetry in the net spectrum is due to the uncorrected spectral extraction error.

b) Cosmic Ray Hits or Other "Emission" Features

Figure 6 shows the response of the fitting and IUESIPS algorithms to an oblique incidence cosmic ray crossing two orders of a high dispersion image. Both the IUESIPS and fitting algorithms are insensitive to isolated emission (or absorption) features and to comparatively narrow features. The IUESIPS filters respond to intermediate width features which are narrower than 31 samples wide, due to the noise characteristics of the background data, which the fitting technique is still insensitive to. Both background handling techniques are sensitive to broad features, either in "emission" or "absorption". The IUESIPS filters respond locally and contaminate the net spectrum at the wavelength of the feature more than does the fitting function. Since the fitting approach has no way to distinguish unflagged broad features from valid structure in the background, the fit can be noticeably distorted, although typically at a lower level than is seen in the IUESIPS smoothed background. The impact of such fitting difficulties on the net spectrum depends upon the amplitude of the background compared to the gross spectrum, and, of course, the scientific interests of each investigator. For those cases where a significant scientific impact occurs, improved net spectra can be achieved by interactively excluding the hit-contaminated portion of the spectrum from the fit, and then using the fit coefficients to reconstruct a smooth background in the absence of the hit.

c) Telemetry Dropouts, Pings, and Camera Target Rings

Experimentation with spectra containing telemetry dropouts, and microphonics "pings" suggests that the response of the fitting function to short duration dropouts and pings intersecting small portions of the spectrum is similar to narrow cosmic ray hits. Telemetry dropouts covering a larger fraction of the inter-order background, or pings affecting much of the background can result in fitted backgrounds which bear little resemblance to the true background level, and produce contaminated net spectra. The current IUESIPS filtered background handling technique suffers from similar limitations. At present, improved backgrounds can be achieved by interactively excluding dropout or ping contaminated data from the background fit. Since the location of telemetry dropouts is recorded in the science image header, we have requested a change to IUESIPS so that these features can be automatically recorded in the data quality (ϵ) record for each order, with different flags for contamination of the gross and inter-order background records. Once this is implemented, exclusion of dropout-contaminated data from the fit can be automated.

Archival high dispersion LWR spectra frequently have the spectral extraction continuing beyond the useful science data and crossing the camera target ring. This effect introduces positive and negative spikes into the beginning and end of the inter-order background (see Figure 7). The current IUESIPS filtering algorithm closely follows these spikes. The fitting algorithm is somewhat more sensitive to the presence of spikes in these locations than elsewhere in the order, undoubtedly due to the coincidence of a large number of zeroes of the various Chebyshev polynomials used in the fit. As a result, the fitted background deviates from a running mean background over distances large compared to the extent of the camera target ring in the inter-order background. This situation can be remedied by interactively trimming the target ring features from gross and inter-order background spectra prior to fitting the background, and results in no loss of science data. We are requesting that IUESIPS similarly modify the extraction for any high dispersion spectra to be reprocessed.

6. EFFECT ON THE ABSOLUTE CALIBRATIONS

We have made a preliminary evaluation of the effect of changing only the background smoothing technique on the low dispersion absolute calibration. Net spectra for three calibration spectra of HD 60753 for each camera (LWP 3938, 4122, 4558, LWR 17691, 17692, 17751, and SWP 25367, 25388, 25398) were generated using both the IUESIPS filtered background, and the Chebyshev polynomial fitted background. Reseaux-contaminated data were replaced by linear interpolations from adjacent uncontaminated data. Following correction, the net spectra generated with each background handling technique were averaged, and then binned on at 25 Å grid to be compatible with the inverse sensitivity data. We find that the difference in the SWP data longward of 1150 Å is negligible, being 0.1% or less. The LWR and LWP binned data show larger differences. From 1850-2500 and longward of 2950 Å the differences in the LWR are as large as 1%. Differences as large as 2% are present in the LWP data shortward of 2300 Å, and longward of 3300 Å. Given the other systematic errors in the low dispersion absolute calibration, and the limited number of spectra included in our study, we conclude that the existing inverse sensitivity data can be used with the background fitting technique without a major degradation of data quality or accuracy.

Time constraints have precluded a systematic evaluation of the effect of changing the background handling technique on high dispersion data, except to note that the effect is likely to be negligible for optimally exposed portions of spectra obtained with low backgrounds. Inspection of Figure 5 suggests that use of the background fitting technique will result in some changes in the ripple parameters K and α (α is likely to increase) if explicit fits to the full blaze function are made (Grady *et al.* 1989). If the Barker (1984) technique is used to derive ripple parameters, we anticipate smaller changes in the ripple data since spectral extraction errors, rather than background handling artifacts dominate in the region of order overlap.

7. SUMMARY

The spurious spectral features noted by Grady *et al.* (1989) can be eliminated from IUE extracted spectra by replacing the current median and mean filtering of the off-order background by fits to low order polynomials. We have investigated the suitability of using a set of 5-7 of the lowest order Chebyshev polynomials to fit off-order backgrounds for large and small aperture spectra obtained with all three of the IUE cameras in routine use. We find that using such a set of polynomials results in good fits to the background for a wide range of IUE spectra. Large improvements in net spectra quality occur for spectra which have the gross spectrum only a few times the amplitude of the off-order background spectrum. We find at most a small effect on the low dispersion absolute calibration, indicating that the Chebyshev polynomial fitting technique could replace the current IUESIPS background filtering technique for current and archival spectra. Preliminary timing tests indicate that the Chebyshev polynomial fitting technique is slightly faster than the currently implemented median and mean filters, implying that there will be no impact on current IUESIPS production processing throughput.

We recommend that the fitting technique replace the current IUESIPS inter-order background handling technique since it eliminates the introduction of spurious spectral features into weakly exposed net spectra.

We would like to thank Dr. Karl W. Cox for valuable discussions on the relative merits of splines and fitting techniques, as well as for assistance with the FORTRAN code implementing least squares fitting using a set of basis functions.

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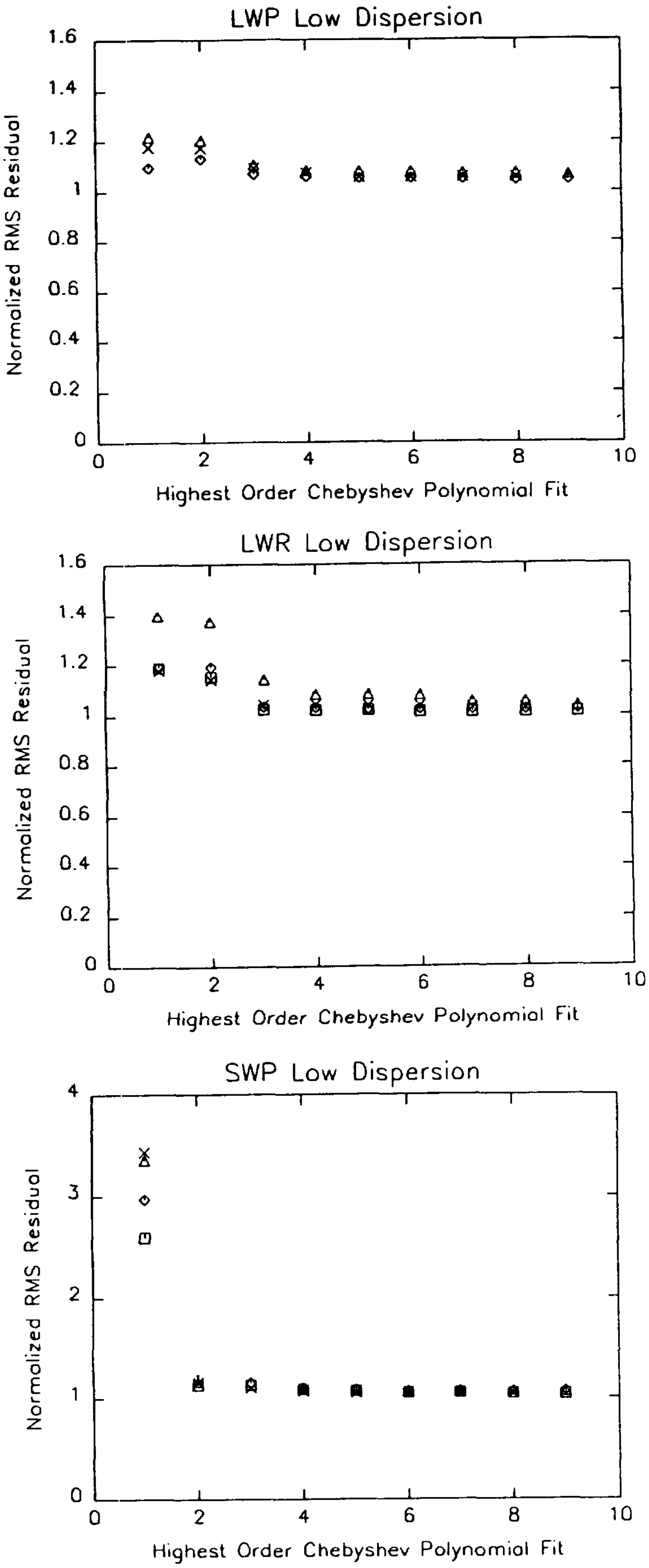

Figure 1: RMS residuals for selected low dispersion backgrounds as a function of the highest polynomial order T_n included in the Chebyshev polynomial fit. Residuals for each spectrum have been normalized by dividing by the rms residual for the IUESIPS smoothed background for that spectrum

a) LWP: Large aperture spectra LWP 14103 (BD +28 4211) and 13000 (BD +75 325) and small aperture spectrum LWP 13600 (HD 60753, indicated by X).

b) LWR: Large aperture spectra LWR 13245 (BD +28 4211), LWR 14539 (BD +75 325), and 13122 (HD 60753) with small aperture spectrum LWR 13122 (HD 60753, indicated by X).

c) SWP: Large aperture spectra SWP 34743 (BD +75 325), 34277 (BD +28 4211), and 34243 (HD 60753) with small aperture spectrum SWP 27384 (HD 93521).

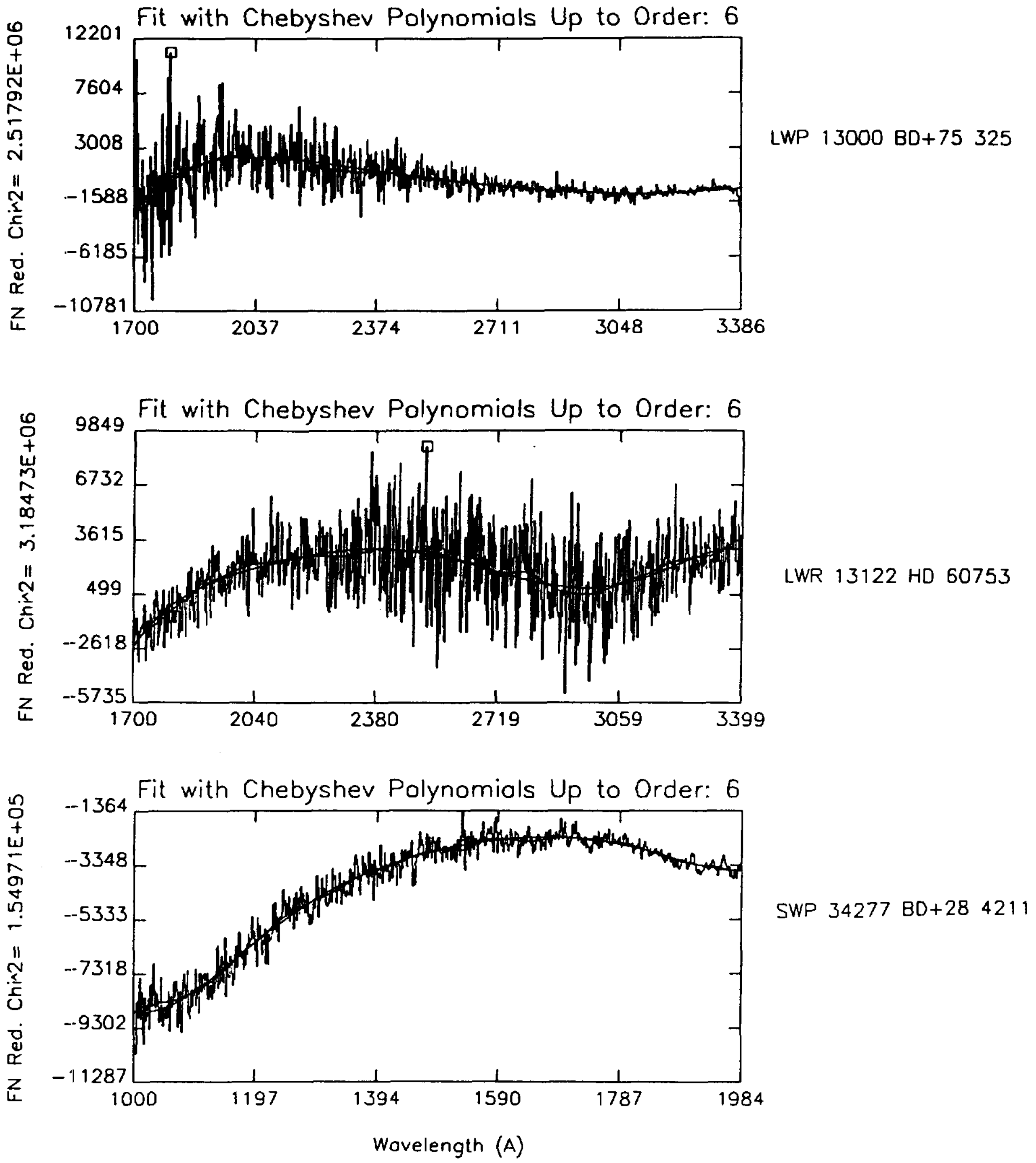

Figure 2: Comparison of IUESIPS and Chebyshev polynomial fitted backgrounds for representative optimally exposed low dispersion large aperture spectra. The noisy curve in each panel is the unsmoothed off-order background stored in the MELO (4th) file for each spectrum. The smoother curve which still contains structure on scales of 100 Å or so is the filtered IUESIPS background. The smoothest curve in each panel is the result of Chebyshev polynomial fits to the off-order background including polynomials T_0 through T_6.

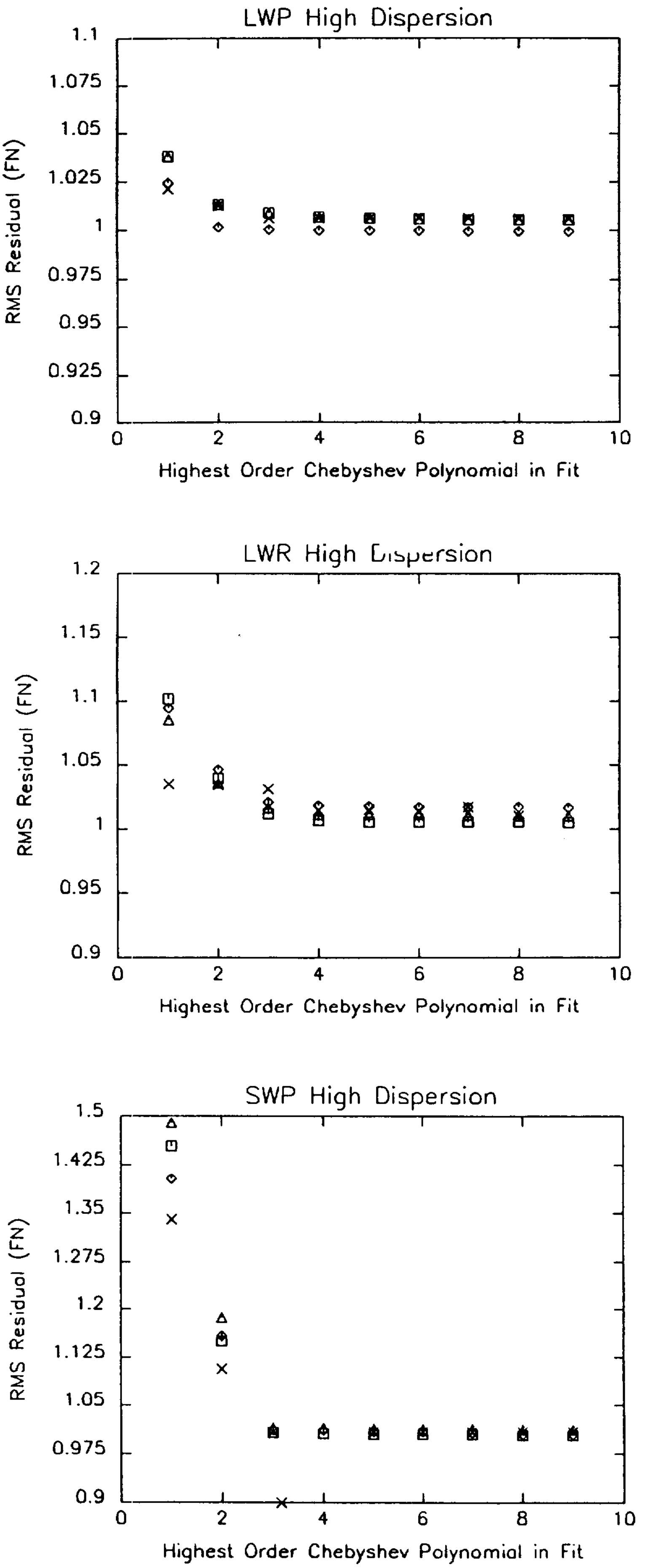

Figure 3: RMS residuals for selected high dispersion backgrounds as a function of the highest polynomial order T_n included in the Chebyshev polynomial fit. Residuals for each spectrum have been normalized by dividing by the rms residual for the IUESIPS smoothed background for that spectrum

a) LWP: Order 100 for large aperture spectra LWP 13691, 13694, and 13703 (η UMa) and small aperture spectrum LWP 12952 (HD 93521, indicated by X).

b) LWR: Order 100 for large aperture spectra LWR 12978, 13121, and 13247 (η UMa) with order 75 of small aperture spectrum LWR 1920 (AB Aur, indicated by X).

c) SWP: Order 100 for large aperture spectra SWP 32651, 33416, and 33859 (η UMa) with small aperture spectrum SWP 33178 (HD 93521).

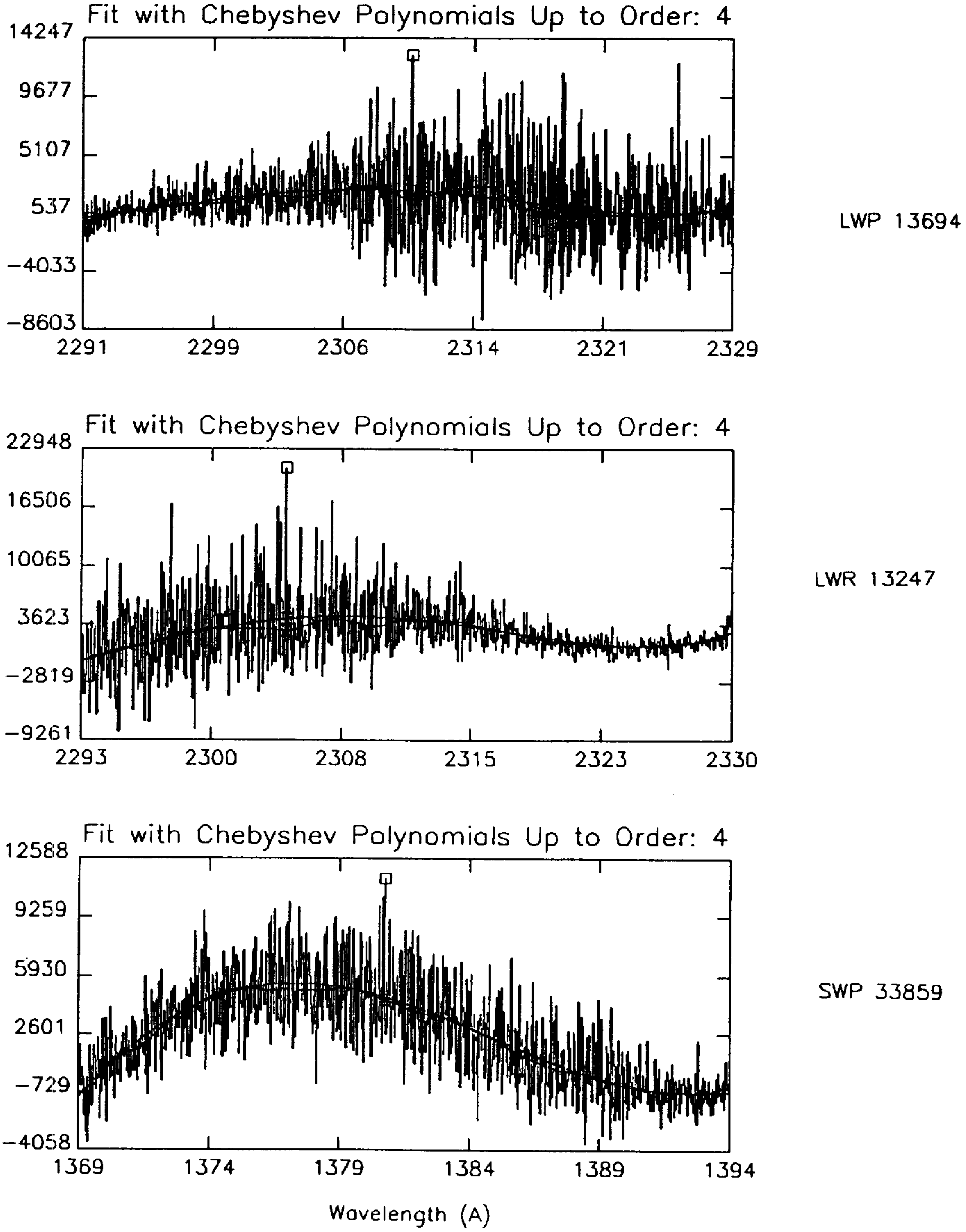

Figure 4: Comparison of IUESIPS and Chebyshev polynomial fitted backgrounds for representative optimally exposed low dispersion large aperture spectra from order 100. The noisy curve in each panel is the unsmoothed off-order background stored in the MEHI (3rd) file for each spectrum. The smoother curve which still contains structure on scales of 3-5 Å or so is the filtered IUESIPS background. The smoothest curve in each panel is the result of Chebyshev polynomial fits to the off-order background including n=0 through n=4.

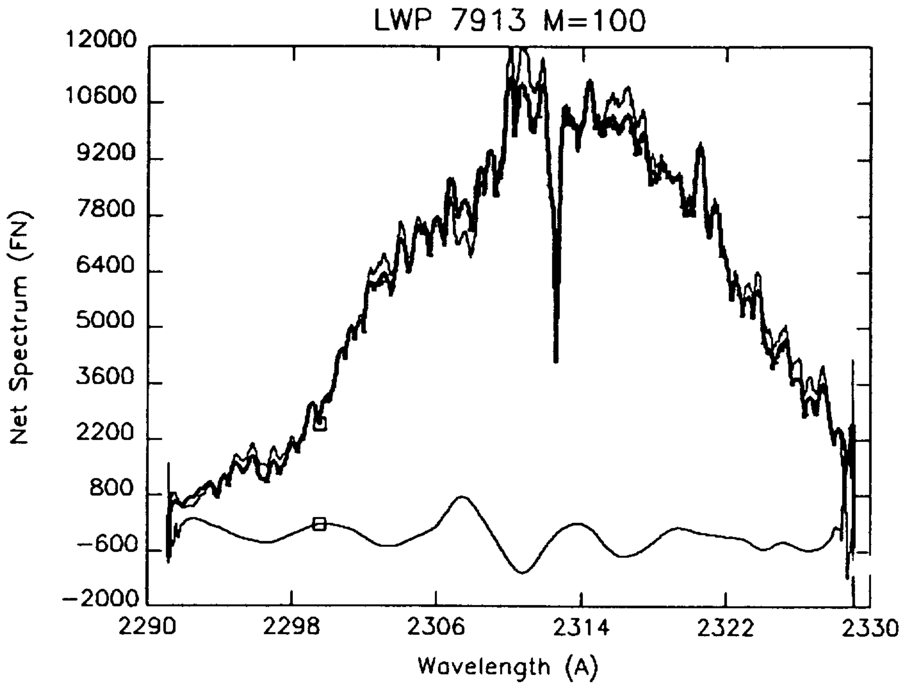

Figure 5: Comparison of net spectra generated with the Chebyshev polynomial fitted background (dark line) and the current IUESIPS smoothing technique (light line) for order 100 of LWP 7913. Both net spectra have been smoothed by 5 and 9 point running mean filters to emphasize the systematic differences in the spectra. An unsmoothed difference spectrum is shown at the same scale at the bottom of the plot. LWP 7913 is an optimally exposed (at 2800 Å) spectrum of η UMa which is weakly exposed near 2300 Å . The difference introduced in the net spectra is typical of the differences seen in weakly exposed portions of high dispersion spectra in general.

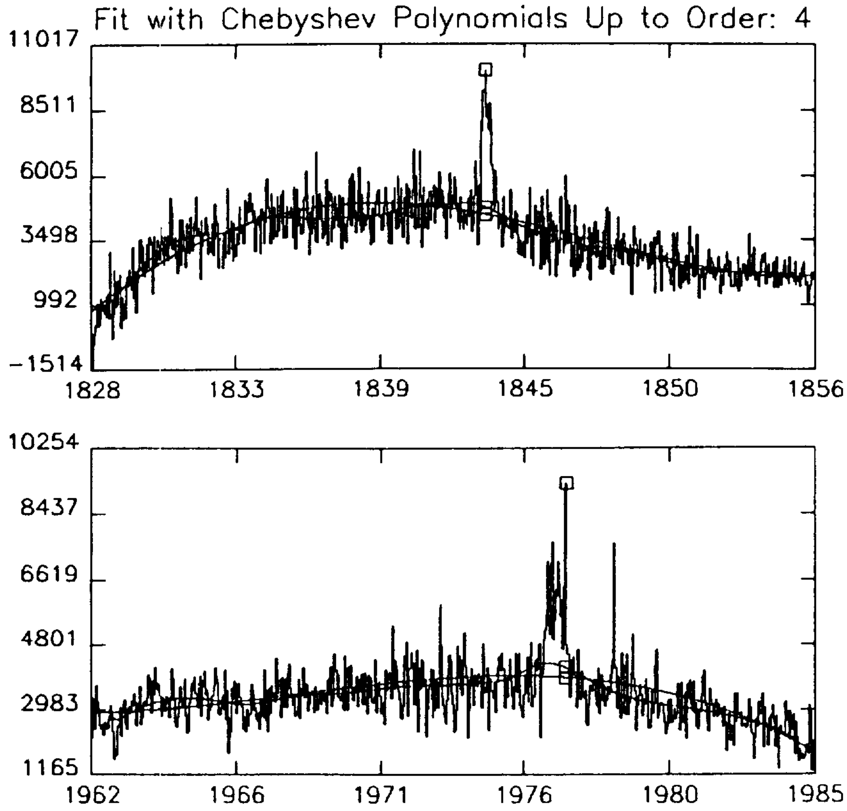

Figure 6: Oblique incidence cosmic ray crossing backgrounds in orders 75 (upper) and 70 of SWP 35674 The Chebyshev polynomial fit responds significantly only when the hit has a full width of ≈1 Å. The IUESIPS fit shows a more localized response to the hit.