STIS Signal-to-Noise Capabilities in the Ultraviolet[1]

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ABSTRACT

The Space Telescope Imaging Spectrograph (STIS) was designed as a versatile spectrograph for the Hubble Space Telescope (HST) capable of maintaining or exceeding the spectroscopic capabilities of both the Goddard High Resolution Spectrograph (GHRS) and the Faint Object Spectrograph (FOS) over the broad bandpass extending from the ultraviolet (115 nm) through the visible (1 μm). STIS achieves performance gains over the aforementioned first generation HST instruments primarily through the use of large (1024×1024) areal detectors in both the ultraviolet and visible regions of the spectrum. Simultaneous spatial and spectral coverage is provided through long slit or slitless spectroscopy of extended sources. A substantial spectral multiplexing advantage is achieved for ultraviolet echelle spectroscopy. This paper will focus on the key issue of signal-to-noise performance with the STIS ultraviolet detectors. Spectra obtained during the first few months of operation, illustrate that high signal-to-noise spectra can be obtained while exploiting STIS's multiplexing advantage. From analysis of a single spectrum of GD153, with counting statistics of ~ 165, a S/N of ~ 130 is achieved per spectral resolution element in the FUV for a flat fielded spectrum. Without flat fielding, a S/N of ~ 85 is achieved. In the NUV a single spectrum of GRW+70°5824, with counting statistics of ~ 200, yields a S/N of ~ 150 per spectral resolution element for the flat fielded spectrum. Without flat fielding a S/N of ~ 100 is achieved. An even higher S/N capability is illustrated through the use of the fixed pattern (FP) split slits in the medium resolution echelle modes. Observations of BD28°4211 yield a signal-to-noise of ~ 250 and ~ 350 per spectral resolution element over an extended spectral region in the FUV and NUV, respectively. For the same spectral region, the signal-to-noise without the application of a flat, or the use of specialized iterative solution, yields a S/N of $\sim$205 in the FUV and $\sim$290 in the NUV. The corresponding S/N from pure counting statistics is $\sim$285 in the FUV and $\sim$380 in the NUV. Selective regions of the BD28°4211 echelle spectrum with suitable counting statistics yield ever higher S/N ratios. These higher S/N of $\sim$390 in the FUV and $\sim$380 in the NUV, are quoted for narrow spectral regions spanning a small areal extent on the detector and may not reflect the S/N capability over the full detector. These results verify that STIS is capable of achieving a S/N in excess of 100:1 per spectral resolution element in both the first order and echelle modes.

Subject headings: HST, STIS, instruments, detectors, MAMA, ultraviolet, spectroscopy, signal-to-noise

1. INTRODUCTION

The Space Telescope Imaging Spectrograph (STIS) is a second generation Hubble Space Telescope (HST) instrument, which was designed as a versatile imaging spectrograph capable of providing spatially extended wavelength coverage from the far ultraviolet (115 nm) to the near-infrared (1 μm) (Woodgate et al., 1998). Spectrograph versatility, provided by the large complement of slit/grating/detector combinations, hinges upon STIS's two dimensional detectors in both the ultraviolet and the visible. The large advances provided by STIS in comparison with the first generation HST spectrographs, the Goddard High-Resolution Spectrograph (GHRS) and the Faint Object Spectrograph (FOS), stem from the use of two dimensional imaging detectors. In both the visible and the ultraviolet, STIS provides simultaneous spectral and spatial coverage with long slit or slitless spectroscopy of extended sources. In addition, a substantial spectral multiplexing advantage is provided by using large areal detectors for echelle spectroscopy in the ultraviolet. STIS echelle modes offer 20-35 times greater simultaneous wavelength coverage than corresponding GHRS modes.

Coverage of this extensive bandpass is accomplished through the use of three detectors. In the far ultraviolet, a 1024×1024 element Multi Anode Microchannel Array (MAMA) detector with a CsI photocathode provides coverage from 115-170 nm. The near ultraviolet detector is also a 1024×1024 MAMA detector, but with a Cs_2Te photocathode providing coverage from 115 to 310 nm, with 165-310 nm as the primary bandpass. Both photon counting MAMA detectors have $25 \times 25\,\mu$m pixels with ∼0.025 arcsec pixel^{-1}, no read noise, and visible light rejection. The MAMA detector QE in combination with the visible light rejection of the photocathode provides higher throughput than would be realized with a CCD in combination with a visible blocking filter. The throughput of a combined CCD Woods filter system has been shown to be of order 2% in the FUV compared to

18% throughput for the FUV MAMA at the peak of the Woods filter bandpass. This combination of low background, high QE, and visible light rejection is critical for UV astronomy where the sources, in general, are faint and often dominated by the visible region of their spectra. In the visible (305 nm - 1μm), STIS employs a 1024×1024 pixel CCD providing a 50 arcsec field-of-view in the spatial direction at 0.05 arcsec pixel^{-1}.

Despite the clear advantage in selecting the MAMA detectors for their aforementioned performance characteristics, there was some concern over their long term pixel-to-pixel stability. This concern was driven in part by the excellent heritage of GHRS for producing high signal-to-noise spectra. Now that STIS would be replacing GHRS as the high resolution spectrograph aboard HST, at a minimum it needed to meet its specification of a signal-to-noise of 100:1 per resolution element (2×2 pixels) to fill the vacancy for high-resolution, high signal-to-noise UV spectroscopy. It was hoped that the detectors would perform far better than this. However, the use of the UV MAMAs in STIS is the first use of this detector technology as a long term astronomical imager aboard a space platform and one of the first uses of any microchannel-plate based UV detectors in a high signal-to-noise long term application.

Flat field images were acquired during ground-based calibration of the instrument. A few, non-optimal, flat field images have been acquired in flight; a more optimal set is scheduled for near term acquisition. During the Servicing Mission Orbital Verification (SMOV) program immediately after launch, a handful of stellar spectra emerged which could be used as a signal-to-noise testbed in addition to the primary function of the data. Since signal-to-noise characterization is not the primary purpose of these spectra, in general, a single spectrum does not have the counting statistics required to test the STIS signal-to-noise capability at levels much greater than 100:1. However, these spectra illustrate that in both the FUV and NUV STIS can achieve a signal-to-noise in excess of 100 per spectral resolution element (a 2 pixel element in the spectral direction with a spatial extraction height of 11 pixels). Thus, these data sets place a lower limit on the UV signal-to-noise capability of STIS (Kaiser et al., 1997). A SMOV proposal dedicated to testing the S/N capability of STIS in the UV by evaluating echelle spectra of BD28°4211 using the FP split slits, yields a S/N of ∼250 in the FUV and ∼350 in the NUV per spectral resolution element (Kaiser et al., 1998).

Thorough reviews of the STIS design and in-flight performance can be found in Woodgate et al., 1998 and Kimble et al., 1998. In Sections 2 through 5 we present details of the detector behavior and the construction of the reference flats. Of greater general interest is Section 6, in which we present the resulting signal-to-noise for some representative observations.

2. Detector Considerations

The large number of STIS optical modes and the limited lifetime of the on-board UV continuum lamps necessitates the acquisition of flats at a limited number of central wavelengths spanning the spectral format. These flats are then applied to both high and low resolution modes.

Given the limited heritage of the MAMA detectors prior to the ground-based science calibration of STIS, it was not known if the flat fields would be wavelength dependent. Also unknown, but of more concern, was the dependence of the FUV flat fields upon the optical mode due to variations in the angle of incidence on the detector. The different STIS modes illuminate the appropriate MAMA detector over a range of angles spanning several degrees.

Due to detector design differences, incident angle effects were expected to be more pronounced for the FUV MAMA. Both detector systems consist of a MgF_2 entrance window which is indium sealed to an evacuated body containing the photocathode, a curved Micro Channel Plate (MCP), and a 1024×1024 anode array. In the NUV MAMA the semitransparent Cs_2Te photocathode is located directly on the inside of the detector window and is proximity focussed to the MCP; a 0.25 mm gap separates the window and the MCP. It is not expected that the photocathode response would be sensitive to small variations in incidence angle (near normal incidence); furthermore the optical path through the MgF_2 window varies only slightly over the small range of incidence angles of the different modes. On the other hand, the FUV MAMA has the photocathode deposited directly on the MCP and has the MgF_2 window located far (~15 mm) from the MCP surface. A repeller wire is provided to force any photoelectrons produced by the MCP web into the MCP pores. In turn, this necessitates coating the inside surface of the MgF_2 window with a ~75Å thick 90% transmissive chrome layer to mitigate any dielectric charging that would cause non-uniformity in the repeller electric field. Irregularities in the window surface resulting from the quality of window polish and transmission variations associated with the granulation inherent in chrome vacuum depostions with $\lesssim$100Å thickness were a concern because the range of incident angles for the different modes, coupled with the large window to MCP distance, results in the illumination of different spatial regions on the detector window. These spatially dependent irregularities could create variations in the transmitted optical beam which could then be amplified by the incident angle dependence of the QE responsivity of the photocathode coated MCP pores.

3. Flat Field Acquisition Strategy

The internal UV continuum lamps are a limited resource where lamp lifetime is determined by the rate of photopolymerization of contaminants onto the lamp window, a process which is accelerated at shorter wavelengths. This situation is exacerbated by the fact that acquisition of flat fields with large format, count-rate limited detectors requires a significant investment of time. Acquiring one flat field with a signal-to-noise of 100:1 per pixel over the entire detector format at a single grating position consumed 13 hours. This is an optimal result: a mode with uniform illumination of the detector, a count-rate well-matched to the detector bright object protection limits, and with minimal exposure overheads. Consequently, in preparation for the STIS ground-based, thermal vacuum, science calibration program, a strategy for acquiring the flat fields was devised (Bohlin et al., 1996). This methodology was motivated by the need to minimize the consumption of two precious commodities, time in the vacuum chamber and the limited lifetime of the on-board UV continuum calibration lamps, while meeting the STIS flat field specification.

The flat field strategy as initially implemented during the ground-based science calibration consisted of obtaining flat fields in the medium resolution modes (G140M and G230M) with a signal-to-noise ratio of 100:1 per resolution element at several pre-defined central wavelengths. This method would check the wavelength dependence, which was estimated to be small. A pixel-to-pixel detector flat field (S/N $\sim$100:1 per pixel) would be acquired at a single wavelength with the internal lamp to provide a baseline for flat field stability at the pixel scale. High signal-to-noise flight flats would then be executed at two or more central wavelengths as determined by the wavelength dependence of the ground flats.

Internal lamp use was limited to the integration time required to acquire a NUV pixel-to-pixel detector flat and to establish the stability of the flat fields at a single central wavelength (mode G230M, λ2659) over a long baseline. Furthermore, comparison of the flat field acquired with the internal lamp to the flat field acquired with the external lamp would establish the validity of acquiring the ground-based NUV flats with an external source.

Contemporaneous analysis of the NUV flat fields acquired with both internal and external lamps during ground-based science calibration verified that the NUV flat fields were neither wavelength nor mode dependent, thus verifying the acquisition strategy for the NUV. In addition, the deep exposures with the internal deuterium lamp at a single central wavelength (λ2659) confirmed that the flat field was stable over a 21 day baseline. It is this ground based flat field that is used to evaluate the S/N of the post-launch NUV spectra.

Analysis of the FUV flats indicates they are also wavelength independent with respect to high frequency pixel-to-pixel variations. As a result, this discussion of the FUV flat field will focus on the potential optical mode dependence of the flat field which drove the FUV flat field acquisition program. Initial flats acquired with the external lamps in the medium resolution modes exhibited mode dependencies that were probably due, in part, to the illumination characteristics associated with the optical feed system for the external lamps which resulted in poor spatial illumination of the detector with the long slit flats. This motivated a change in the ground-based acquisition strategy for the FUV flat fields. It was still necessary to acquire the flats using external sources, if possible, due to the limited lifetime of the internal krypton lamp. Consequently, the ground-based FUV flats were acquired in the echelle modes where the demand for high signal-to-noise spectroscopy would be greatest and where any off-axis illumination effects associated with the external optical delivery system would be minimized through the use of short ($0.5''$) echelle slits. The inter-order gaps were illuminated by tilting the cross-dispersion grating by a small amount corresponding to $0.5'$ on the detector. The ground-based FUV flat was constructed from echelle spectra (modes E140M and E140H) using external argon, krypton, and xenon lamps to span the spectral format. These echelle flats were combined with an initial set of long-slit first-order (modes G140L and G140M) post-launch flats. The post-launch flats were acquired at non-optimal grating settings but were capable of improving the count statistics in regions that were masked in the ground flats due to emission lines in the *external* flat field continuum lamps and in the remaining small inter-order gaps in the echelle flats.

Non-uniformities in the detector illumination of the post-launch flats are a result of initial non-optimal selections of the observing mode and central wavelengths, slit irregularities, and command development not yet implemented. A revised flat field calibration program has begun execution whereby the central wavelength has been optimized to provide full spectral illumination of the detector at a nearly uniform count rate, slit widths have been matched to maximize the global count rate, and commanding has been implemented to step the slit in the spatial direction thus providing illumination in the spatial regions nominally blocked by the slit fiducials.

4. Flat Field Construction

The overall strategy is to separate the illuminating lamp signature from the high frequency structure of the MAMA flat itself. To accomplish this, corrections are made for slit width variations, spectral emission features inherent in the lamp spectrum, and the overall spectral illumination pattern. These corrections are described in more detail throughout this section.

The introduction of a correction W(y) for slit width variations can correct all but the largest defects in the NUV to 1% precision. The 1-D function W is the raw flat data image collapsed along the spectral direction and is analogous to the orthogonal correction, $S(\lambda)$, which is the average lamp spectrum collapsed along the slit direction and is used to correct the flat field images for narrow emission lines.

In addition to the illumination variation resulting from the lamp spectral and spatial response and the slit non-uniformity, there is also a contribution due to the HST Optical

Telescope Assembly(OTA)+STIS vignetting. This low frequency correction awaits analysis of post-launch calibration data. Flat fields acquired with the internal calibration lamps are limited to characterizing the high frequency pixel-to-pixel response of the detector. It is this characterization that is necessary for the detection of weak spectral lines and line profile measurements.

Construction of the flat fields is accomplished by analyzing the data in the high resolution format. This 2048×2048 image format is the result of exploiting the capability of the processing electronics to centroid event positions to half the spacing of the anode array, providing improved sampling and higher resolution (Kasle and Morgan 1991) at the expense of increased odd-even flat field variations.

In practice, the flats are constructed by geometrically correcting the original co-added image to make the dispersion and spatial axes parallel to the x and y axes of the rotated image. Then, the corrected image is collapsed along the separate axes to obtain the spectral S-flat and the spatial W-flat averages. Following this, the inverse geometric distortion correction is applied to transform the WS-flat product image back to the original distorted space. The original image is then divided by the transformed WS-flat template. Slit fiducials, the long-slit occulting bars near the detector edge in the nominal position, are set to unity in the non-dithered flats and other problem regions are then masked. Filtering is applied to the flat to obtain the overall 2-D illumination function (L-flat) for that mode. Division of the flat by the L-flat yields the pixel-to-pixel detector response (P-flat) (Bohlin et al., 1997). The L-flat and the P-flat are both normalized to unity. Results are calculated for the flat field variations per resolution element (2×2 low resolution pixels), per low resolution pixel (2×2 high resolution pixels), and per high resolution pixel. Unless explicitly stated otherwise, a pixel refers to one low resolution pixel, ie one pixel in the 1024×1024 image format.

5. Flat Field Evaluation

Evaluation of both the NUV and FUV flat fields is accomplished by quantifying, through the use of an image ratio test, the similarity of each independent flat that was eventually used in the composite flat.

5.1. NUV:

For the NUV flat field, images spanning four months of ground tests were acquired at six different central wavelengths. Each flat at a given wavelength and epoch was evaluated in comparison with the extreme wavelength 2977Å flat with the best statistics. The results are presented in Table 1 where the entries are the one sigma values for ratios of images.

EDITOR: PLACE TABLE 1 HERE.

The first set of data presented is for a 512×512 flat field image. This image is binned to consist of 2×2 pixel resolution elements. The 1024×1024 image is for the nominal low resolution pixel format. The 2048×2048 image is in the high resolution format. From the increased amplitude of the residuals, it is clear that the gain in sampling and resolution for the high resolution readout mode extracts a penalty in the form of increased variations in the flat field.

The first row for each of the three image sizes is the expected sigma from counting statistics, the second row is the actual scatter in the ratio images, and the third row measures the actual difference between the two ratioed images. In other words, the third row of each set reflects the actual scatter with the Poisson uncertainty removed in quadrature. The results are consistent with no wavelength dependence and little MAMA contribution to the scatter per low resolution pixel or per resolution element. There is a residual scatter of a few percent in the high resolution ratios, which demonstrates the nearly complete removal of the large 60% pixel-to-pixel variation of the high resolution flats. Since the tabulated Poisson statistics utilize the average counts, the Poisson contributions for the high resolution case are underestimates because of the large change in sensitivity between adjacent pixels due to the odd-even effect in the MAMA electronics. The corresponding high resolution residuals are overestimates.

EDITOR: PLACE FIGURE 1 HERE.

Ground-based NUV flats were obtained during two distinct time intervals. The first data set was obtained during August and September 1996 while in thermal vacuum at Ball Aerospace. After shipping the instrument to GSFC, a second set of flats was acquired under nitrogen purge during November 1996. The two sets of flats exhibit residual structure as illustrated most strongly in the high-res residual of 9.81% in the last row of Table 1. The other P-flat data obtained in November 1996 is at 2419A and also has a high residual of 9.22% per high-resolution pixel at image center. It is possible that this residual is due in part to the different thermal environment during the ground-based thermal vacuum flat field acquisition at Ball Aerospace and the ambient nitrogen purge environment at GSFC. In the high resolution mode, small changes in the MCP gain induce changes in the high resolution pixel-to-pixel variations. For the low resolution mode, the small gain change in the MCP has a negligible effect in the flat field pixel-to-pixel variations (Argabright, et al., 1998). From Table 1, the low resolution pixel and resolution element residuals are below 0.8% and 0.5%, respectively, when comparing the flat fields acquired in the GSFC environment to the earlier thermal vacuum flat fields.

Flat field illumination with the external deuterium lamp does not completely fill the slit at the shortest wavelengths of 1769Å and 1933Å. Consequently, these images were only used for completeness in testing the wavelength independence of the flat field. The NUV superflat is the combination of the data at the G230M central wavelengths of 2176, 2419, 2659, and 2977A and is shown in Figure 1. The Poisson statistic of 0.30% per resolution element for the superflat corresponds to a S/N=333 in regions without fiducial or slit defect masks.

5.2. FUV:

For the FUV flat, images at each central wavelength for a specific optical mode were combined and evaluated, through an image ratio test, with the other flats in the same mode. No wavelength dependence was observed. However, the limited wavelength coverage provided by each of the external calibration lamps results in a less spatially comprehensive test of the wavelength dependence than is achieved in the NUV where the illumination from the deuterium lamp spans the entire spectral format.

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The optical mode dependence of the FUV flats was evaluted by comparing the combined flat for each mode to the mode G140L combined flat using an image ratio test. The results are tabulated in Table 2. From the third row for each of the three image sizes, we note that the residuals do not differ dramatically between optical modes. Calculating the residuals for an extracted spectral resolution element (11×2 low resolution pixels), weighted by a gaussian profile in the cross dispersion direction, yields residuals of 0.97%, 0.92%, and 0.80% for the ratio of the G140L flat to the G140M, E140M, and E140H flat fields, respectively. There is some residual scatter which may limit the achievable signal-to-noise for some high signal-to-noise, low resolution, programs which do not employ additional techniques such as dithering or FP split slits to further reduce the high frequency flat field variations. For the echelle flats the image ratio is testing the pre-launch to post-launch residual as well. The combined FUV superflat has a Poisson derived S/N $\gtrsim$ 500 per resolution element for the central columns of the detector not affected by masks or small residual inter-order gaps. At the detector edges the S/N decreases to $\gtrsim$150 per resolution element.

EDITOR: PLACE FIGURE 2 HERE.

From a visual inspection of the flat field ratios it is apparent that there is a residual effect in removing an overall moiré pattern from the FUV flat field. The amplitude of the residual moiré pattern is $\lesssim$ 6% peak-to-peak. The pattern is visible in both the NUV (Figure 1) and FUV (Figure 2) flats, but is more pronounced in the FUV flat field.

This pattern probably arises from the difference between the periodicity of the MCP grid and the anode array grid which are in proximity focus, typical separations between the two arrays are of order 50 - 100 microns (Timothy et al., 1989). If this is the origin of the moiré pattern, it is expected that temperature differences between observations may result in shifts in the pattern (Argabright, et al., 1998, Joseph et al., 1998). From lab tests, two low-resolution flat field exposures with a difference of 28°C in the MAMA tube temperature exhibited an 8% peak-to-peak variation in the moiré pattern when ratioed. This variation was only 2% peak-to-peak for exposures where the MAMA tube temperature varied by 7°C.

STIS's initial thermal design called for the MAMA temperature to be held within a 1°C range near 20°C. However, due to higher than expected aft shroud temperatures for the HST (Woodgate et al, 1998) and operational modifications resulting from the susceptibility of STIS opto-isolators to respond to high energy particle induced transients (Kimble et al, 1998) , the operating temperature of the FUV MAMA may vary by ∼7°C from one observation to the next.

6. Signal-to-Noise Results

The signal-to-noise was evaluated for three separate cases, a single spectrum of a point source, multiple spectra of a point source, and spectra acquired using a fixed pattern (FP) split slit method, whereby spectra are acquired at the same spatial location but are shifted spectrally on the detector. It is important to distinguish between these cases due to the additional smoothing provided by coaddition of non-coincident spectra.

In practice, the calibration pipeline employs a spectral extraction height of 11 pixels in the spatial direction and the spectral resolution is nominally two pixels. Therefore the S/N quoted for a point source, as defined in this paper, is per spectral resolution element (11×2 low resolution pixels) unless noted otherwise. This extraction height encompasses 60% - 80% of the energy, depending upon the optical mode and wavelength. However, the signal-to-noise specification is per resolution element, implying a 2×2 low-resolution element. The relative transmission of the 2 pixel to 11 pixel spatial extraction heights in the FUV are ∼45% at 1423Å for mode G140L and ∼56% at 1367Å for E140M. In the NUV, the relative extraction height throughputs are ∼60% at 2371Å for G230L and ∼69% at 2616Å for E230M.

EDITOR: PLACE FIGURE 3 HERE.

For the case of a single point source spectrum, spectra of GRW+70°5824 in mode G230L (Figure 3) and GD153 in mode G140L were flat fielded to determine the realizable S/N. Initially the data were extracted, then background subtracted, and binned by 2 low resolution pixels in the spectral direction. The 1-D spectrum was then partitioned into segments composed of 20 bins. Each segment was fit with a three-node cubic spline. A three-node spline was used because it provided a good fit to the data without being too sensitive to small scale fluctuations in the data. Consistent results were obtained with fits performed using 15-30 bins per segment. Twenty bin segments were fit, in general, because they provide enough bins for a robust fit while minimizing the number of segments impacted by spectral features. Each segment was divided by its fit; the mean and standard deviation were calculated and ratioed to determine the S/N for each segment. At this resolution, spectra of these targets is expected to be devoid of spectral features. Hence comparison of the observed spectrum to a low-frequency fit to that spectrum provides an assessment of the effectiveness of the pixel-to-pixel rectification of the data. Any real spectral features in the data would reduce the apparent signal-to-noise. Thus, as long as we don't employ too high an order fit to the data, the results here should represent lower limits to the signal-to-noise capabilities of STIS.

The average of the S/N over the spectral segments contained within the specified spectral range is tabulated in Table 3 for the NUV and Table 4 for the FUV. For the NUV MAMA, the GRW+70°5824 spectrum has a peak potential S/N, corresponding to pure counting statistics, of ∼200 per spectral resolution element. The realized S/N is ∼105 *without the application of a flat field* and ∼150 after application of the NUV flat field. For the FUV MAMA, the GD153 spectrum has a peak potential S/N, corresponding to pure counting statistics, of ∼165 per spectral resolution element. The realized S/N is ∼85 *without the application of a flat field* and ∼130 after application of the FUV flat field.

EDITOR: PLACE TABLE 3 HERE.

To further test the S/N limit in the FUV, with improved count statistics, six G140L spectra of GRW+70°5824 (Figure 4) were coadded. No shifts were applied to align the spectra. Over the region extending from 1347-1502Å the S/N of the composite spectrum is ∼180, with S/N ∼300 from pure counting statistics. It should be cautioned however that these spectra are neither spatially nor spectrally coincident, exhibiting an offset of ∼10 pixels spectrally and ∼4 pixels spatially. Consequently a single spectrum of comparable count statistics may yield a slightly lower S/N. These results are also presented in Table 4. For the FUV spectral range extending from 1502Å through 1657Å, in both GD153 and GRW+70°5824, the counting statistics are poorer thus limiting the signal-to-noise.

EDITOR: PLACE TABLE 4 HERE.

Further inspection of the results indicates that at S/N ∼180 the composition of the flat may become important. To achieve a S/N in excess of this, it may be required to use a flat composed solely from the same mode as the observations to eliminate residual angle of incidence effects in the flat. Or, spectra acquired using the FP split slits may be required. It is also possible that the pre-launch data (E140M and E140H) does not flatten the observations as well as the post-launch flats.

EDITOR: PLACE FIGURE 4 HERE.

Because it was not known whether the ground flats would be valid post-launch, and acquisition of post-launch flats would require a significant investment of lamp lifetime, a proposal was executed to test the signal-to-noise capabilities of the UV detectors by acquiring a data set which could be iteratively solved for both the stellar spectrum and the flat field simultaneously. To maximize the areal illumination on the detector while minimizing both observing time and spectral features, observations of BD28°4211 were obtained in echelle modes E140M and G230M. This data set (HST proposal 7091) was analyzed using both the iterative technique (Bagnuolo and Gies 1991, Lambert et al. 1994) and by employing the ground-based flats.

These echelle data sets were subject to two forms of smoothing. Doppler shifting of the input spectrum due to HST's orbital motion smooths the detector responsivity (real-time Doppler compensation in the on-board image accumulation maintains spectral resolution). While the Doppler compensation for an individual exposure did not exceed 1 high-resolution pixel, the compensation for the set of exposures spanned ± 3 high-resolution pixels thus smoothing the detector responsivity by this magnitude for the data set. The second form of smoothing arises from acquiring the data through a set of five, FP split, apertures which offset the spectrum by incommensurate amounts in a purely spectral direction on the detector. Coaddition of the offset spectra smooths the detector responsivity. For this test, only integral pixel shifts were permitted so that interpolation effects would not artificially improve the signal-to-noise.

For the standard analysis each spectrum was first background subtracted. Next, the flat field was smoothed by the same amount as the on-board Doppler compensation for that single image. Then the doppler smoothed flat was applied to the stellar spectrum. As with the first order modes, an 11 pixel extraction height was used to extract the spectra. The spectra were then binned by 2 low-resolution pixels in the spectral direction. Each spectral order was partitioned into segments comprised of 20 bins each. Each segment was then divided by a three-node spline-fit to the data. Given the high resolution of the data it was sometimes difficult to distinguish between weak absorption features and variations in the continuum that could be instrumental in origin. In the FUV, the numerous spectral features result in isolated continuum regions that span a relatively small spatial extent on the detector. To mitigate any bias toward isolated detector regions with unusually smooth detector responsivity, the signal-to-noise results from several spectral regions in multiple orders were averaged to provide a realistic assessment of the signal-to-noise capability. In the NUV, where spectral lines were few, the signal-to-noise is calculated for a broad spatial band spanning the blaze peak for a given order.

EDITOR: PLACE FIGURE 5 HERE.

The S/N achieved using echelle (Doppler compensated) spectra with the FP split slits and the pipeline flats, is $\sim$250 in the FUV and $\sim$350 in the NUV. As a result of averaging the S/N for several spectral regions in the FUV, some isolated spectral regions with appropriate counting statistics yield a significantly higher signal-to-noise than the quoted 250 per spectral resolution element. It should be noted that without using any flat at all, the same spectral regions yield a S/N of 200 in the FUV and 290 in the NUV. The counting statistics for these regions are 285 in the FUV and 385 in the NUV.

Figures 5 and 6 illustrate the quality of spectra obtained using the FP split slits. Both figures represent a single order with high counting statistics. The NUV spectrum (Figure 5) is devoid of spectral features, whereas the FUV spectrum of BD28°4211 has numerous spectral features as illustrated in Figure 6. The average signal-to-noise for the regions designated on the plots is 280 in the FUV and 340 in the NUV.

EDITOR: PLACE FIGURE 6 HERE.

The FP split slit observations of BD28°4211 were also analyzed using an iterative technique which permits solving the data for both the target spectrum and the flat field response of the instrument (Gilliland et al., 1998). These observations were designed to satisfy the requirements imposed by the iterative analysis technique. Consequently these observations consist of multiple (37 total for each band over the 5 separate FP split slits) short exposures for which on-board Doppler compensation does not exceed one high-resolution pixel. These individual exposures, which are offset to many different positions on the detector, are used to separately constrain both stellar and detector flat-field features at a resolution of one low-resolution pixel. The particular technique used here is a modification of the Bagnuolo and Gies (1991) formalism for separating spectra of binary star components shifted by relative Doppler motion, to a formalism for separating stellar and detector response imposed features following from FP split observations (see Lambert, et al. 1994 for use with GHRS spectra). The brightest order in the FUV and NUV echelle spectra with Poisson limited counting statistics of about 470 and 400 respectively, per spectral resolution element (7×2 low-resolution pixels) at the order peak were selected for generating a full, iterative separation of detector and stellar features. The FP split slit offsets with STIS span $0.5''$ or about 20 low-resolution pixels, therefore the FP slit solution will only work well for data with lines significantly sharper than 20 pixels which is the case for the orders analyzed. The technique iteratively solves for both the shifts necessary to register both the (1-d) flat-field and the stellar features of these independent spectra. For both the FUV and NUV, a S/N slightly in excess of 350 per spectral resolution element is found for the single isolated region on the detector analyzed using this technique. In this iterative solution the starting data consisted of the extracted low-resolution spectra for each individual exposure, without use of prior flat field information.

Given the consistency of the results when reducing the FP split slit data by the aforementioned techniques, it is advantageous to employ the pipeline flat rather than to solve iteratively for the flat from the stellar spectrum. The prime advantage lies in the duty cycle for acquiring the spectra. The iterative method relies upon the individual spectra being unadulterated by Doppler compensation. This requires relatively short exposures for targets with declinations within $\pm 30^\circ$ of the plane of the HST orbit. For the high resolution echelle modes these exposures become prohibitively short, with the orbital visibility period dominated by detector readouts. There is no Doppler smoothing constraint imposed when using the pipeline flat. Consequently, the time required to achieve the required counting statistics is less. In addition, use of the pipeline flats is much more robust against realities of the stellar spectra, than attempting to obtain FP-split iterative separations. The iterative technique fails if the stellar spectrum contains repetitive features that happen to be offset by the characteristic spacing of the FP-split slits (degeneracy in the Fourier domain), or if relatively large sections of the stellar spectra have very low count levels (e.g., broad saturated lines) such that offsets large enough to exchange spectral regions containing good information on flat field structure have not been provided. The GHRS was more flexible in this particular since the cadence of offsets could be designed with explicit knowledge of the spectrum to be observed (Lambert et al. 1994). Furthermore, the iterative technique involves a generally (but not always) convergent process that may take some knowledgeable guidance to obtain reasonably optimal results.

Simulations of the high resolution echelle modes E140H and E230H indicate that the Doppler compensation, up to ± 12 high-resolution pixels, effectively smooths the detector responsivity sufficiently to achieve a signal-to-noise per resolution element of 330 in the NUV and 140 in the FUV *without a flat* assuming a typical Doppler amplitude of ± 8 high-resolution pixels. Use of the FP split slits in the high resolution echelle modes will further smooth the detector responsivity and should yield an even higher S/N than predicted with pure Doppler smoothing.

7. Conclusion

In the year since launch, STIS has performed well. Its UV MAMA detectors have been stable. No detector based sensitivity losses have been observed. Both long slit low resolution first order spectra and medium resolution echelle spectra illustrate that STIS is capable of achieving a signal-to-noise well exceeding 100:1 per spectral resolution element in the NUV and FUV. A single point source low resolution flat fielded spectrum of GRW+70°5824 in the NUV has a S/N of ∼150 per spectral resolution element; without flat fielding a S/N of 100 is realized. In the FUV, a single flat fielded point source spectrum of GD153 has a S/N of ∼130 per spectral resolution element; without application of a flat a S/N of 85 is achieved. The realized S/N is probably limited by counting statistics in the stellar spectrum for both observations. Co-adding spectra in the FUV achieves a S/N ∼180 which is probably limited by either the optical mode content or pre to post-launch shifts in the flat. Even higher S/N capabilities have been demonstrated through the use of the FP split slits in the Doppler compensated, medium resolution echelle modes where co-added BD28°4211 spectra exhibit a S/N in excess of ∼250 in the FUV and ∼350 in the NUV per spectral resolution element when using either the pipeline flats or the iterative analysis technique. Pipeline analysis without a flat field yields a S/N of 205 in the FUV and 290 in the NUV. Significantly higher S/N ratios have been measured in the FUV for isolated spectral regions. From the limited data available since launch, STIS has proven it can provide a S/N capability in excess of 100:1 in both the NUV and FUV.

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Captions to figures

Fig. 1.— The wavelength independent NUV reference flat, which is comprised solely of ground-based flat field images. Individual frames at several central wavelengths spanning the range from 2176 Å to 2977 Å were combined to generate this flat. Unilluminated regions at the detector corners are the result of vignetting by a baffle at the window of the NUV MAMA.

Fig. 2.— The FUV reference flat which is comprised of both pre-launch (modes E140M and E140H) and post-launch (modes G140L and G140M) data spanning a wavelength range from 1150 Å to 1700 Å.

Fig. 3.— This single spectrum of GRW+70°5824 has been flat fielded using the pipeline (ground-based) NUV reference flat. For the spectral range from 2167 Å to 2520 Å, a signal-to-noise of 150 is obtained. In this region pure poisson statistics yield a signal-to-noise of ∼200, whereas analysis of the data without flat fielding yields a signal-to-noise of ∼100 per spectral resolution element.

Fig. 4.— Coaddition of long slit spectra of GRW+70°5824 in the FUV yields a spectrum with poisson statistics of ∼300 per spectral resolution element over the spectral region extending from 1347 Å to 1502 Å. Flat fielding the spectra results in a signal-to-noise of ∼180 over this same spectral region. Analysis of the data without a flat results in a signal-to-noise of ∼90 per spectral resolution element.

Fig. 5.— A single flat fielded order of the echelle spectrum of BD28°4211. For the region illustrated on the figure, a signal-to-noise of ∼340 has been achieved. Without flat fielding, a signal-to-noise of ∼290 was obtained. A signal-to-noise of ∼380 is expected from Poisson statistics alone.

Fig. 6.— A single order of the flat fielded FUV spectrum of BD28°4211, illustrating the numerous spectral features which limit one's ability to identify a spatially extended continuum region for evaluation. The average signal-to-noise for the regions indicated in the figure is 380 from pure Poisson statistics and 280 per spectral resolution element for the flat fielded spectrum. Without flat fielding a signal-to-noise of 215 is achieved.

Table 1: Statistics for the Ratio of NUV Flat Fields to the 2977Å Flat (All Mode G230M)

Central Wavelength	1769	1933	2176	2419	2419	2419	2659	2659	2659	2659	297
Date	9/11/96	9/11/96	8/29/96	8/29/96	9/1/96	11/12/96	8/23/96	8/26/96	8/30/96	11/22/96	9/1/9
P FLATS (512x512)											
Poisson (%)	1.23	1.38	1.33	2.05	1.50	1.99	1.05	1.65	2.09	1.25	2.0
Actual sigma (%)	1.24	1.41	1.33	2.04	1.50	2.02	1.07	1.64	2.07	1.33	2.0
Resid. sigma (%)	0.20	0.27	0.00	0.00	0.02	0.38	0.19	0.00	0.00	0.46	0.0
P FLATS (1024x1024)											
Poisson (%)	2.45	2.77	2.67	4.09	2.99	3.98	2.10	3.29	4.18	2.50	4.1
Actual sigma (%)	2.47	2.80	2.67	4.02	2.99	4.01	2.12	3.31	4.17	2.63	4.1
Resid. sigma (%)	0.29	0.42	0.12	0.00	0.11	0.56	0.34	0.31	0.00	0.80	0.0
P FLATS (2048x2048)											
Poisson (%)	4.91	5.53	5.33	8.18	5.98	7.95	4.19	6.59	8.35	5.00	8.
Actual sigma (%)	5.72	6.47	6.15	8.96	6.89	12.18	4.87	7.25	9.63	11.01	9.
Resid. sigma (%)	2.95	3.34	3.05	3.66	3.42	9.22	2.48	3.04	4.79	9.81	4.

Table 2: Statistics for the Ratio of the FUV G140L Flat Field to the Flats from Other Modes

	G140M	E140M	E140H
P FLATS (512x512)			
Poisson (%)	1.61	1.10	0.75
Actual sigma (%)	2.02	1.72	1.37
Resid. sigma (%)	1.20	1.32	1.15
P FLATS (1024x1024)			
Poisson (%)	3.23	2.20	1.49
Actual sigma (%)	4.02	3.16	2.47
Resid. sigma (%)	2.39	2.27	1.96
P FLATS (2048x2048)			
Poisson (%)	7.14	5.16	3.63
Actual sigma (%)	11.23	11.65	9.07
Resid. sigma (%)	8.67	10.45	8.31

Table 3: NUV Signal-to-Noise Capabilities for a G230L Point Source Spectrum

Star	Spectral Class (B Mag)	Exposure Time	Flat Composition	Spectral Range	S/N (Counting Statistics)	S/N
GRW+70°5824	DA3	636.0	NO Flat	1698 - 2167	<165>	<100>
	(12.63)			2167 - 2520	<204>	<101>
				2520 - 3050	<163>	<102>
			G230M	1698 - 2167	<165>	<154>
				2167 - 2520	<204>	<149>
				2520 - 3050	<163>	<152>

Table 4: FUV Signal-to-Noise Capabilities for a G140L Point Source Spectrum

Star	Spectral Class (B Mag)	Exposure Time	Flat Composition	Spectral Range	S/N (Counting Statistics)	S/N
GD153	DA1	187.1	NO Flat	1280 - 1458	<165>	<85>
	(13.07)			1502 - 1657	<75>	<65>
			G140L	1280 - 1458	<165>	<113>
				1502 - 1657	<75>	<50>
			G140L + G140M	1280 - 1458	<165>	<116>
				1502 - 1657	<75>	<73>
			E140M + E140H	1280 - 1458	<165>	<127>
				1502 - 1657	<75>	<74>
			G140L + G140M + E140M + E140H	1280 - 1458	<165>	<128>
				1502 - 1657	<75>	<75>
GRW+70°5824	DA3	1260.0	NO Flat	1347 - 1502	<295>	<93>
	(12.63)			1502 - 1657	<172>	<81>
			G140L	1347 - 1502	<295>	<184>
				1502 - 1657	<172>	<92>
			G140L + G140M	1347 - 1502	<295>	<189>
				1502 - 1657	<172>	<130>
			E140M + E140H	1347 - 1502	<295>	<168>
				1502 - 1657	<172>	<150>
			G140L + G140M + E140M + E140H	1347 - 1502	<295>	<182>
				1502 - 1657	<172>	<155>