

# Cosmic Origins Spectrograph: Flat Fields And Signal-to-Noise Characteristics

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The Cosmic Origins Spectrograph (COS) employs different microchannel plate detectors for its two channels: a cross delay line (XDL) for the FUV, and a multi-anode microchannel array (MAMA) for the NUV. These detectors show non-uniformities due to the intrinsic 'chicken wire' and moire patterns of the microchannel plates, dead spots, hot regions, and for the XDL, shadowing by the quantum efficiency (QE) grid wires. Signal-to-noise (S/N) improvements can be achieved by applying a high-quality flat field during data reduction. For the highest S/N, multiple exposures can be taken using the FP-POS technique, where spectra are stepped to different locations on the detector. During the COS Servicing Mission Observatory Verification (SMOV) program, observations of bright astronomical targets and an internal deuterium lamp were made in both channels to investigate methodologies to improve the S/N of on-orbit observations. For the NUV channel, flat field exposures were obtained with the onboard lamp. Comparisons with a flat field constructed from prelaunch data indicate that there have been no changes, and a high S/N flat has been built by combining ground and flight data. Analysis indicates that S/N = 100 per pixel is achievable using flat fielding alone. For the FUV channel, which does not have a high quality ground flat, exposures were obtained of white dwarfs at various cross-dispersion locations on the detector. Comparisons of different reduction techniques for this data set are presented. Until high-quality flat fields are implemented in standard pipeline processing, high S/N spectra are best achieved by the FP-POS technique, which has demonstrated S/N > 50 per resolution element.

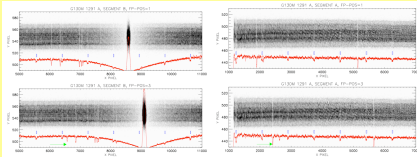


Figure FUV-1. Sample regions of the flat field mapping exposures illustrating the on-orbit technique. Images are observations summed from 5 cross-dispersion locations, causing irregular illumination along Y. The red lines show data collapsed in Y. The two FP-POS settings cause spectral features intrinsic to the star to shift to different X locations (green arrow), while detector features remain constant (e.g., grid wire shadows marked by blue lines). Bright emission in segment B is geocoronal Ly $\alpha$ .

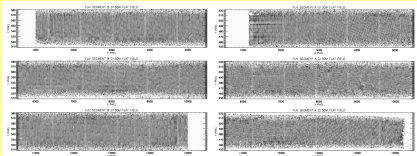


Figure FUV-2. Flat field images for the two FUV segments. Vertical bars are grid wire shadows. Hexagonal patterns arise from multi-fiber packing and pore deformation during microchannel plate (MCP) manufacturing. Moire stripes arise from offsets of pore locations in the stacked MCP plates. Dead spots appear as white holes.

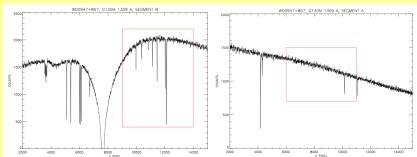


Figure FUV-3. Exposure levels in spectra obtained from the SMOV high S/N program (gross counts per pixel). Red boxes mark areas in figures below demonstrating S/N achieved by different techniques.

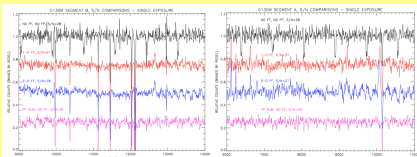


Figure FUV-4. A normalized spectrum of an observation taken at one central wavelength and FP-POS grating setting compared to different S/N improvement techniques. The top spectrum is the uncorrected spectrum, the middle two have been corrected by 1-D and 2-D flat fielding, and the bottom spectrum illustrates an observation with the same exposure time, but taken at four FP-POS positions and merged in wavelength. Spectra are offset by an arbitrary amount for clarity.

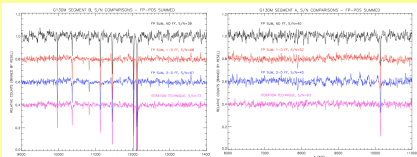


Figure FUV-5. Four FP-POS step-merged spectra corrected by various techniques. Top spectrum is a straight sum of the data in wavelength space (the bottom spectrum in Figure FUV-4). The middle two spectra are merged after flat fielding is performed on each exposure. The bottom spectrum is the result of self-correction through the iteration technique, without using the flat field image at all. Spectra are offset by an arbitrary amount for clarity.

## FUV On-Orbit Technique

- Thermal vacuum (TV) tests demonstrated S/N improvements are possible by flat fielding, but a high quality FUV flat was not obtained
- An SMOV plan was devised to obtain an improved flat field by mapping out the detector with a bright external target
- WD0320-539 was observed at 5 cross-dispersion positions with G130M, and 2 each with G160M and G140L to sample the whole illuminated detector area. Different central wavelength and FP-POS settings were used at each position
- Data allows the separation of spectral and detector features in the analysis while covering the range of detector Y locations where spectra occur

## FUV On-Orbit Flat

- Flat fields were created for each grating and segment, summing all data in pixel space to average out spectral features
- The spectral slope was removed by polynomial fits normalized to the center of the detector
- Possible flat field changes with event pulse height were characterized and were found to be measurable but small
- The G130M and G160M flats in their overlap region do not match at all locations, indicating a possible illumination angle dependency

## FUV S/N Evaluation

- High S/N observations were made of WD0947+857 (G130M, G140L) and WD1057+719 (G160M)
- Different methodologies were tested to study S/N improvement :
  - FP-POS summing, smoothing out detector structures
  - 2-D correction, dividing by the flat image prior to extraction
  - 1-D correction, extracting a 1-D vector from the flat field image as in spectral extraction, then dividing it into the spectrum
  - Spectral iteration, deriving a spectrum and residual flat from FP-POS exposures alone by summing and ratioing data alternately in pixel and wavelength space

## FUV S/N For A Single Grating Setting

- As expected prior to launch, for observations at one grating setting, even deep exposures are limited by inherent fixed pattern noise of the segments
- Flat fielding is applied pixel-to-pixel, while characterization is measured by resolution element (6 pixel binning)
- Flat fielding removes prominent dips due to grid wire shadowing, but induces some structure with the initially made on-orbit flat
- A 1-D correction is somewhat better than 2-D
- The CalCOS pipeline is set to skip the flat fielding step at this time
- Further improvements in the flat fields are expected and may be installed incrementally

## FUV S/N For FP-POS Exposures

- FP-POS shifting provides the mechanism to improve the S/N by either averaging out detector features or separating them from spectral lines
- A straight sum of FP-POS data show residual grid wire features, but these can be removed by changing data quality vector weights
- A combination of FP-POS summing with flat fielding improves the S/N significantly
- The spectral iteration technique achieves the highest S/N results, but this methodology requires the observations themselves to be of high S/N

## NUV Ground Flat

- Data were obtained during thermal vacuum (TV) testing in 2003 and 2006 with the G185M grating
- The internal D2 lamp was observed through the flat field calibration aperture (FCA)
- An external D2 lamp was observed through the primary science aperture (PSA), moving it in the cross-dispersion direction to map the science area
- Most counts came from the external lamp and were taken in ACCUM mode
- A pixel-to-pixel flat (P-flat) was generated

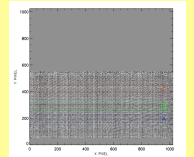


Figure NUV-1. NUV ground flat (P-flat) created from TV data. Only the lower region of the detector, where the three NUV science stripes (A, B, C) lie, is calibrated by design.

## NUV On-Orbit Flat

- Thirty-six 1800-sec internal D2 lamp exposures were taken in SMOV as in TV 2003
- The program was designed to check that the ground flat was still valid after launch
- Image ratios between on-orbit and ground flat indicate alignment is better than 1 pixel
- Detector blemishes are also in the same location, consistent with no detector format shift
- On-orbit and ground data were combined to create a superflat for CalCOS processing

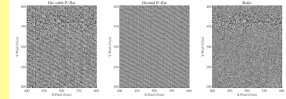


Figure NUV-2. Comparison of a sub-region of the P-flats for the on-orbit and TV test data. Dividing the on-orbit flat by the ground flat yields a salt-and-pepper pattern, indicating the flats are aligned.

## NUV Vignetting

- Observations of external targets show a depression in count rates at the left edge of the detector
- This was traced to vignetting at the camera mirrors after final instrument alignment
- The profile is the same in all three spectral stripes for the M gratings (+/- 2.5%)
- The G230L grating may be slightly different, but higher S/N data are needed
- An average vignetting profile was constructed from M grating data

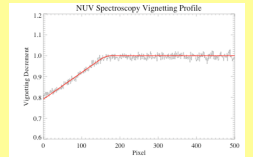


Figure NUV-3. Average NUV spectral vignetting profile based on spectral ratios of FP-POS exposures.

## NUV Combined Flat

- The vignetting profile was incorporated in the NUV P-flat reference file for CalCOS
- COS FLT images have the vignetting removed, but the COUNTS images contain the original count rates
- A change to CalCOS is being made to allow use of different flat fields for the M gratings and G230L
- We are considering modifying CalCOS to use L-flats, which would include the vignetting instead

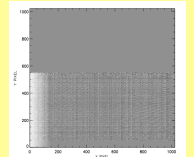


Figure NUV-4. Flat field used in CalCOS pipeline processing, created from all on-orbit and TV data and incorporating the NUV vignetting correction.

## NUV S/N Evaluation

- High S/N exposures were taken of G191-B2B with all M gratings and GD71 with G230L
- Different central wavelengths and all FP-POS settings were used
- The program was designed to achieve S/N > 30 per resolution element for all settings and demonstrate S/N > 100 for at least one setting.
- Studies indicate that the Poisson limit can be reached for S/N < 70. S/N > 150 was demonstrated for the SMOV high S/N program

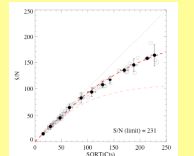


Figure NUV-5. S/N achieved by flat fielding and FP-POS summing vs. Poisson statistics ( $\sqrt{\text{counts}}$ ). Solid points are averages of measurements (gray circles). Thin dashed red line is the S/N for data not co-added from FP-POS spectra.