

NUV Geometric Distortions and Wavelength Calibration

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1. INTRODUCTION

During the initial fabrication and development of the NUV MAMA detector, the team at Ball Aerospace measured amongst other parameters, the geometric distortions on the detector (Ball document SER COS-NUV-001 dated June 3, 1998). We report here on the effect of correcting the geometric distortion on the absolute wavelength determination of observed spectral lines.

2. COS NUV MAMA GEOMETRIC DISTORTIONS

The Figures 2-1a and 2-1b below represents the measured geometric distortions along the X and Y directions respectively where all three axis are in pixels. Figures 2-2a and 2-2b show the average distortions in the dispersion direction (Y) for the WCA and the PSA extraction box positions for each stripe. The maximum combined distortion in the areas of the various WCA and PSA stripes is about 2 pixels (5 pixels over the whole detector). Although the errors are small, they are a significant portion of a resolution element (3 pixels).

To determine if applying the geometric correction is warranted, data from the G185M grating at every central wavelength positions and every stripe were examined. Wavelength solutions for both the raw and the geometrically corrected data were obtained and used to measure the central wavelengths of a list of known PtNe emission lines. The residuals of these measured wavelengths from their known values are used as an indicator of the improvement made by geometrically correcting the data.

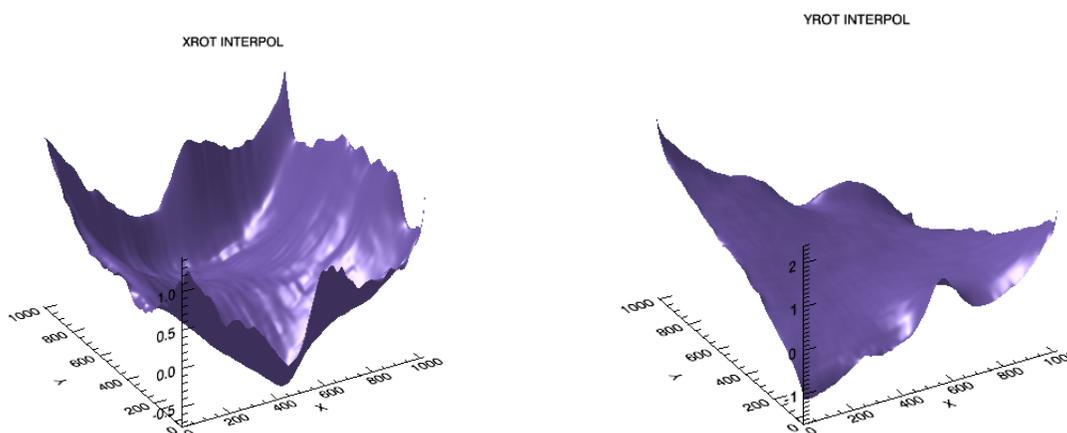


Figure 2-1 The NUV-MAMA geometric distortions along the COS cross-dispersion (a, left) and the dispersion (b, right) directions.

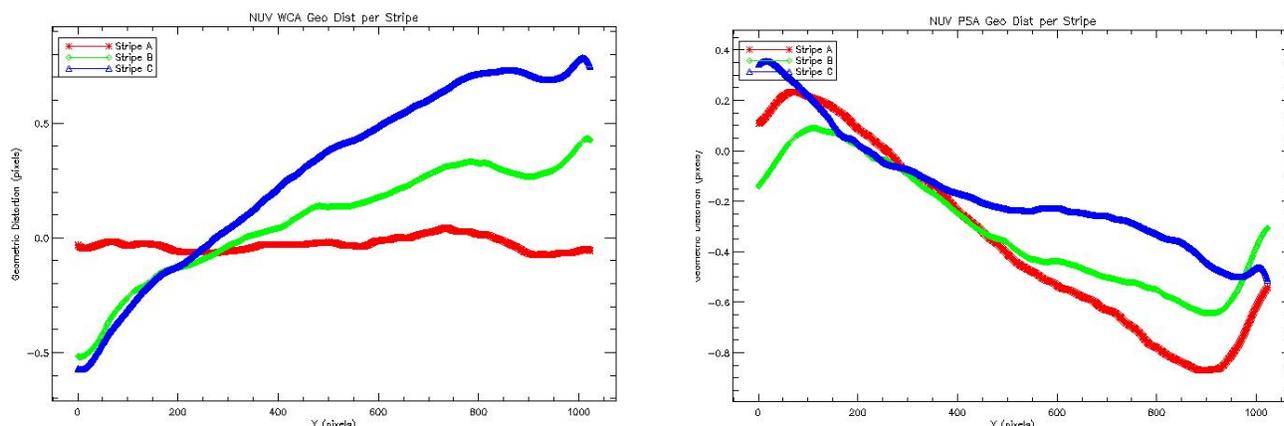


Figure 2-2 Average dispersion-direction geometric distortion values for the 2003 thermal-vac WCA (left) and PSA (right) stripe locations.

3. WAVELENGTH CALIBRATION

The document “COS Calibration Requirements & Procedures” (COS-01-0003) describes the steps to obtain a wavelength calibrated spectrum. The method uses reference files containing the wavelength solutions for the various gratings at all standard central wavelengths for the WCA as well as the known separation between the PSA and WCA spectra on the detector. Science observations through the PSA all have corresponding WCA exposures (either Tag Flash or separate exposures). The method proposes that we measure the offset between the reference file spectra for the WCA and the observed WCA by using a cross-correlation. This offset is then simply added to the PSA spectra Y positions. A wavelength is obtained by applying the reference file wavelength solution coefficients from the WCA to the new Y position of the PSA spectra. The specifications for the wavelength calibration is ± 15 km/s for the medium resolution gratings as described in table 2.2-2 of the document COS-01-0001 (OP-01), and ± 175 km/s for the G230L grating.

Data was obtained through the WCA (with the internal PtNe lamp) and the PSA (using an external PtNe lamp) for all gratings and standard central wavelengths during thermal-vac tests in 2003 and 2006. The alignment of the external calibration system with respect to COS was different in 2006 and 2003 which resulted in a shift of the location of the PSA spectra on the detector between the two datasets. By testing the wavelength solutions from 2003 against the 2003 and the 2006 datasets, we intend to show that PSA dispersion solutions obtained at one alignment can be used to produce accurate wavelength solutions for other alignments.

The current algorithm of shifting the WCA dispersion solutions for use with the PSA stripes is inferior to this solution because:

1. thermal-vac data indicate that the linear term of the WCA and PSA dispersion solutions are slightly different between the internal and external optical paths (on the order of $1\text{ m \AA} / \text{\AA}$ or $\sim 6\text{ km/s}$ over the entire stripe),
2. the geometric distortion in the region of the detector of the WCA stripes is different of that in the region of the PSA stripes, and is frozen into the WCA dispersion solutions, introducing further wavelength errors of ~ 1 pixels (5 km/s).

3.1 TV-2003 DATA

The 2003 spectra for the G185M at all standard central wavelengths (using all three stripes) were used to test the accuracy of the original AV-03 PSA wavelength calibration algorithm (move the WCA solutions to the PSA with a constant wavelength offset). Each PSA spectrum was calibrated using the WCA wavelength solution after adjusting its offset by cross-correlation. Their emission lines were identified and the central wavelengths were compared with the list of PtNe lines published by NIST. Figure 3.1-1 shows the distribution of errors between the calculated wavelengths and what is found in the NIST line list. The standard deviation corresponds to about $\pm 36\text{ km/s}$ at 1850 \AA . Looking at the data more carefully, it is clear that the wavelength solutions obtained from data through the WCA do not apply to the PSA with a simple offset term only.

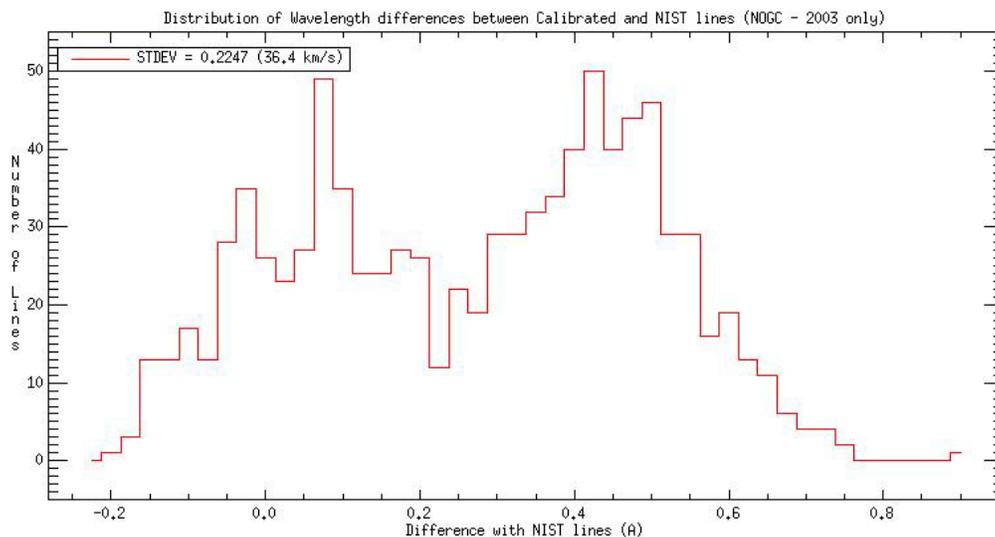


Figure 3.1-1 Residual errors between calculated emission line wavelengths and the list of lines from NIST using the 2003 WCA solutions with the 2003 PSA data.

New wavelength solutions were measured for each of the 2003 central wavelength of the G185M for the PSA. Applying these solutions to the 2003 data as above, we obtain a distribution shown in figure 3.1-2. Since we're using the same 2003 data set, this is a measure of the intrinsic wavelength solution errors only. The standard deviation of 0.0316 Å corresponds to ± 5.1 km/s at 1850 Å.

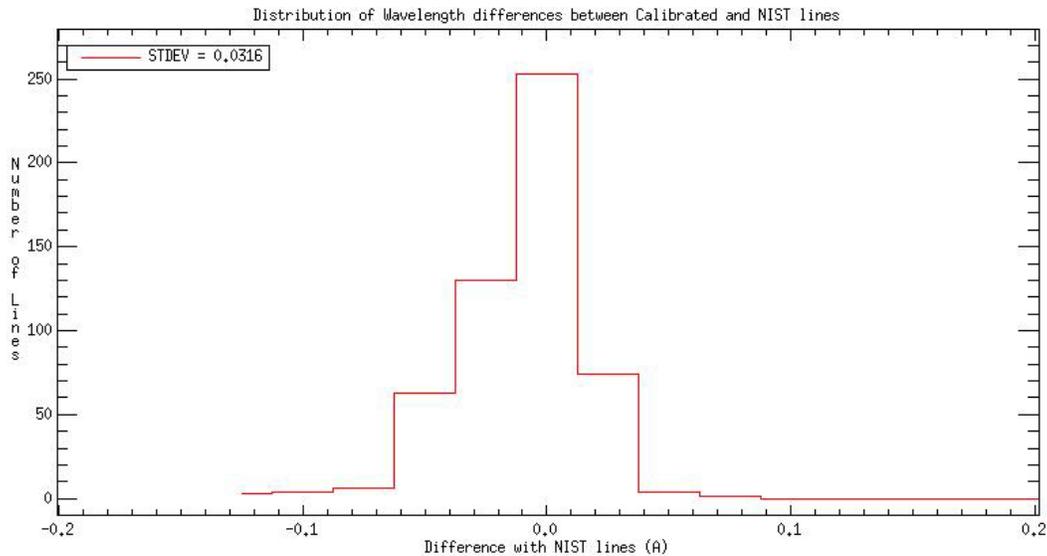


Figure 3.1-2 Residual errors from calculated emission line wavelengths and the list of lines from NIST using the 2003 PSA solutions with the same 2003 PSA data.

3.2 TV-2006 DATA

As a first test to prove that the PSA dispersion solutions can be used to other PSA locations, we applied the 2003 PSA wavelength solutions directly to the 2006 PSA data (after a cross-correlation offset). Figure 3.2-1 shows the distribution of the residual errors corresponding to ± 4.5 km/s at 1850 Å. It is clear from figures 3.1-1 and 3.2-1 that the PSA data requires its own wavelength solution, and that merely shifting the WCA solutions is insufficient.

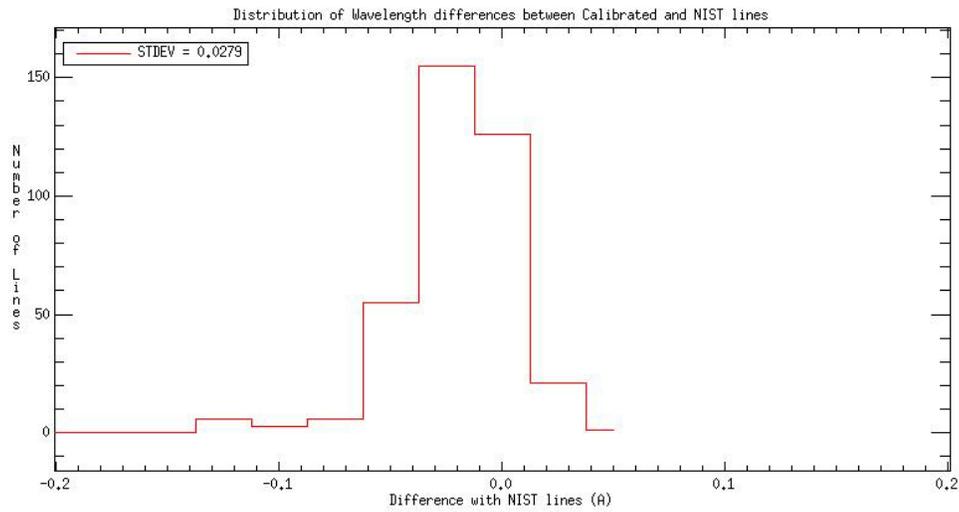


Figure 3.2-1 Residual errors when applying the 2003 PSA solutions to the 2006 PSA data after a simple offset. The residual error is $\pm 0.0279\text{\AA}$ or $\pm 4.5\text{ km/s}$ at 1850\AA .

The wavelength solutions determined for the PSA during ground thermal-vac test in 2003 or 2006 can thus be applied to the PSA data on orbit after taking into account the alignment induced offsets along the dispersion direction. This offset can be inferred from the relative separations of the WCA and PSA. Figure 3.2-2 shows the same specific PtNe emission line through the PSA and WCA for 2003 and 2006 indicating the alignment induced offsets from these two different installations.

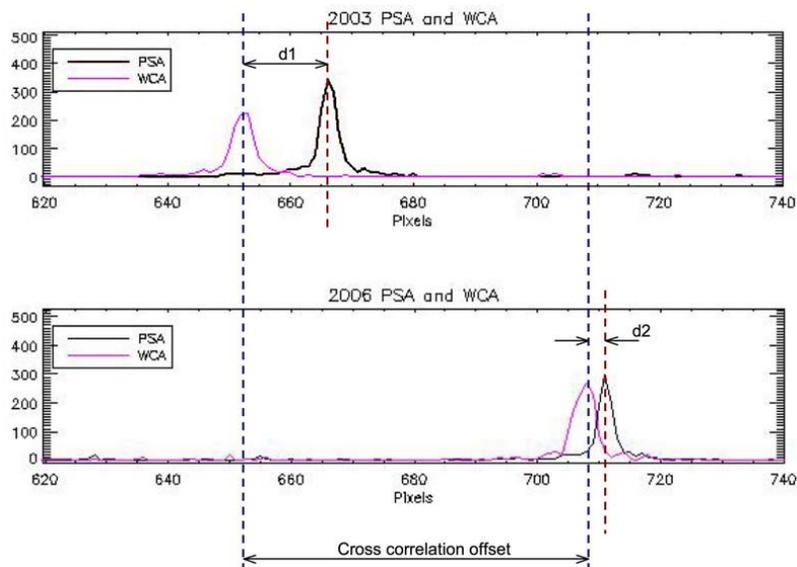


Figure 3.2-2 Various positions of a specific PtNe emission line for WCA, PSA in 2003 and 2006

The WCA-PSA dispersion-direction separation of a given wavelength is wavelength dependant since we determined that the internal and external optical paths have slightly different dispersions. The distance d1 and d2 shown in figure 3.2-2 represent the separation, in pixels, for a specific PtNe observed through the PSA and the WCA for the 2003 and the 2006 data respectively. This separation is plotted in figure 3.2-3a and 3.2-3b as a function of wavelength for all three stripes.

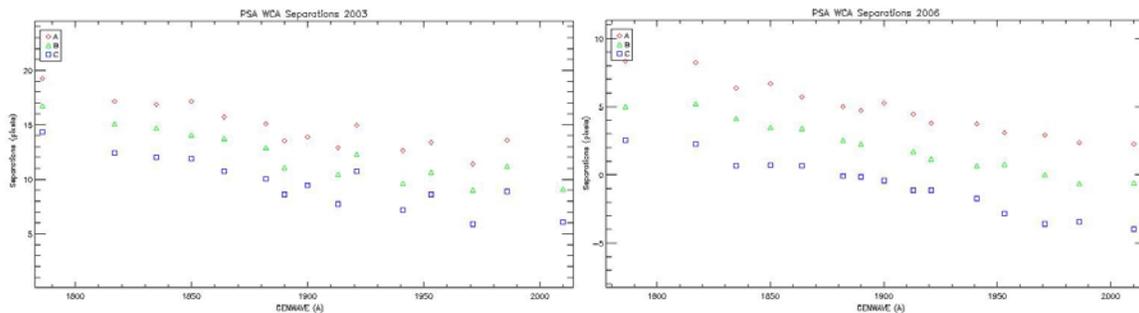


Figure 3.2-3 Variations of WCA-PSA dispersion-direction separations for each stripe, as a function of wavelengths for 2003 (left) and 2006 (right) data.

The differences in these distances from 2003 and 2006 are plotted in figure 3.2-4 and indicate a fairly constant difference as a function of wavelength for each stripe. The data was obtained by cross-correlating the WCA and PSA spectra. The average difference between the WCA-PSA distance in 2003 and 2006 was measured as: 9.8 ± 0.4 pixels for stripe A, 10.1 ± 0.4 pixels for stripe B and 10.4 ± 0.4 pixels for stripe C. This indicates that although the two apertures have different dispersion solutions, these solutions are stable with different COS installation angle with respect to the external source.

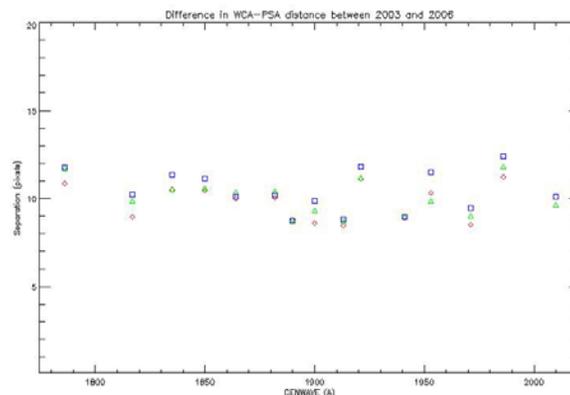


Figure 3.2-4 Dispersion-direction differences in WCA-PSA distance between 2003 and 2006

These values are used in subsequent wavelength calibrations for the 2006 PSA data. Referring to figure 3.2-2 above, we used the 2003 WCA and PSA data to obtain a wavelength solution for the 2006 PSA data. The first step is to measure the displacement in the WCA positions (cross-correlation offset). We then moved the 2006 data to overlap the WCA spectra and then added the average difference between the WCA-PSA for each stripe between 2003 and 2006 measured above. This step aligns the PSA 2006 spectra to the 2003 PSA spectra. We were then able to use the 2003 PSA wavelength solution with the 2006 PSA data. The wavelength for each photon event is then obtained with the relation below (referring to figure 3.2-2) where:

Y_{06} : original dispersion direction pixel location for photons through the PSA
 Y'_{06} : new pixel location aligned, in the dispersion direction, with the 2003 PSA spectra
 CCO : cross-correlation offset between the 2003 and the 2006 WCA spectra
 (d1-d2) : difference in the installation alignment between 2003 and 2006
 PSA_{03} : wavelength solution parameters for the 2003 PSA spectrum

$$Y'_{06} = Y_{06} - CCO + (d1-d2)$$

$$\lambda_{06} = PSA_{03}[0] + PSA_{03}[1] * Y'_{06} + PSA_{03}[2] * (Y'_{06})^2$$

Wavelength calibrated spectra were obtained for the G185M grating for every central wavelength and every stripe for the 2006 PSA data using this method. The centroid of the identified spectral lines were compared with the NIST line list. The distribution of errors is shown in figure 3.2-5. The standard deviation is 0.0434 Å corresponding to ± 7.0 km/s at 1850 Å which is less than half of the specified requirements.

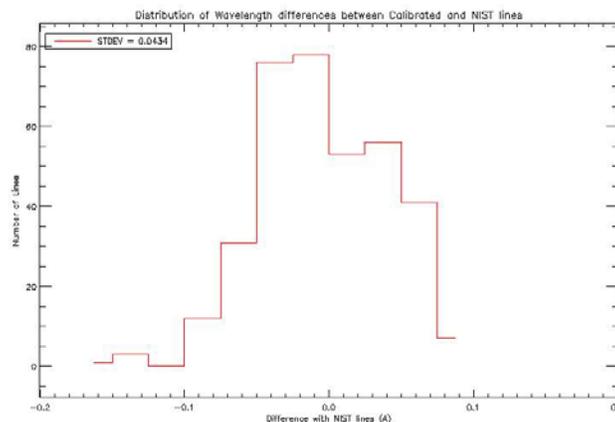


Figure 3.2-5 Measured wavelength errors for 2006 PSA data obtained with the offset 2003 PSA solutions. The standard deviation is 0.0434 Å or ± 7.0 km/s.

4. CORRECTING THE GEOMETRIC DISTORTIONS

The whole dataset for 2003 and 2006 was corrected for the MAMA geometric distortions and new wavelength solutions were measure for the 2003 WCA, PSA and for the 2006 WCA. The same steps described in 3.2 above were used to identify emission lines and obtain residual errors. Figure 4-1 shows the errors in the calculated wavelengths for 2003 PSA when using the wavelength solution obtained from the same 2003 PSA dataset. Like figure 3.1-2 above, this represents the intrinsic uncertainties in the wavelength slution. The standard deviation corresponds to 0.0174 \AA or $\pm 2.8 \text{ km/s}$ at 1850 \AA .

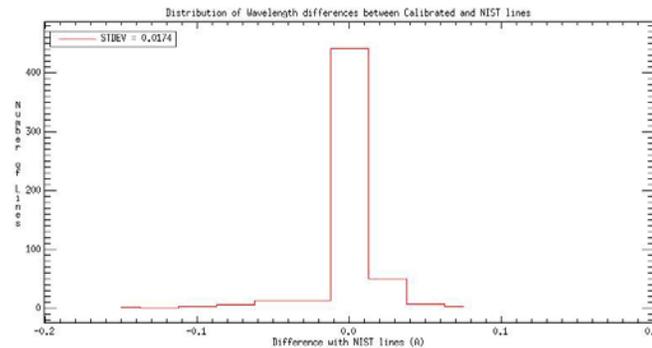


Figure 4-1 Errors in the wavelength solution for the 2003 PSA data. The standard deviation corresponds to 0.0174 \AA or $\pm 2.8 \text{ km/s}$ at 1850 \AA and represents the intrinsic error of our wavelength solution determination method.

Figure 4-2 represents the distribution of wavelength measurement errors when applying the 2003 PSA dispersion solutions data to the 2006 PSA data after geometric correction. We get the same type of errors as in section 3.2 above (0.0455 \AA or $\pm 7.4 \text{ km/s}$) which indicates that no improvement was made in the absolute wavelength calibration by correcting for the geometric distortions.

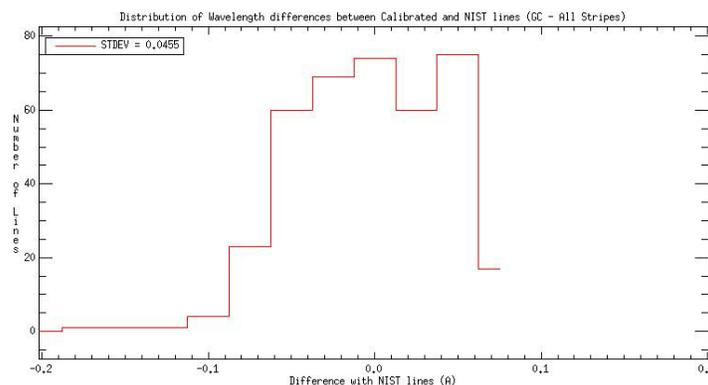


Figure 4-2 Measured wavelength errors after geometric correction.

5. WAVELENGTH UNCERTAINTIES WITH FP-SPLITS

Each standard central wavelength setting has a total of four slightly different grating angle positions (FP-SPLITS). We measured the errors in the wavelengths for all FP-SPLIT positions when applying the standard FP-SPLIT position solution to the other positions. These are plotted in figures 5-1a,b,c. The corresponding errors are ± 5.6 km/s, ± 4.6 km/s and ± 5.6 km/s for the FPPOS positions 1, 2 and 4 respectively (note that FPPOS=3 is the standard central wavelength). These values are almost identical as what was obtained for the FPPOS=3 and well within the specifications.

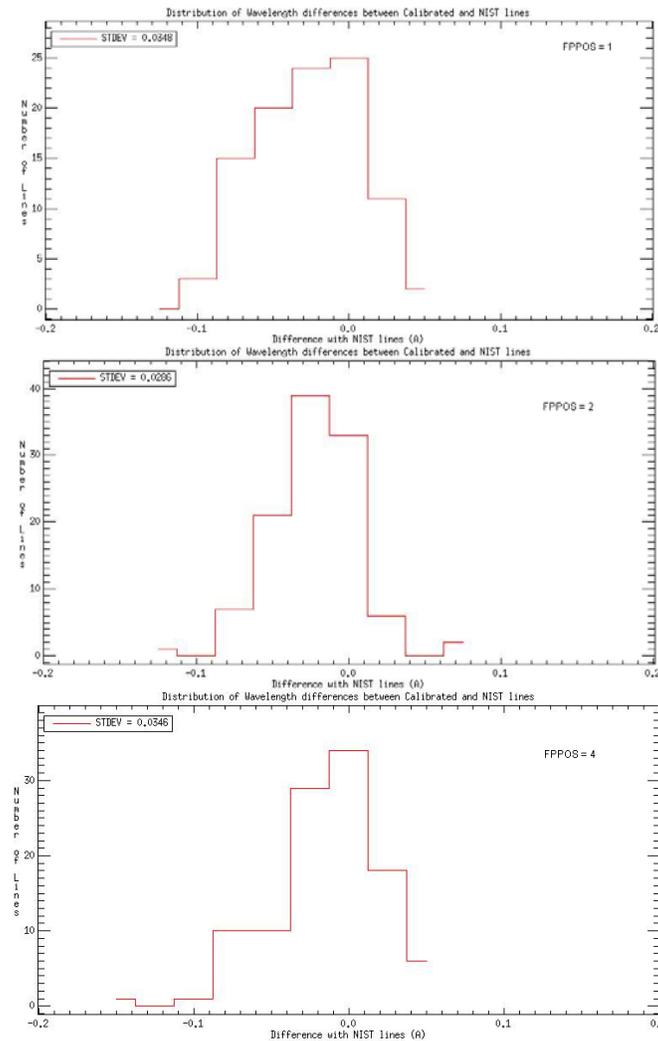


Figure 5-1 Wavelength calibration errors for the FPPOS=1 (a, top), FPPOS=2 (b, middle) and FPPOS=4 (c, bottom).

6. CONCLUSION

From the two thermal-vacuum test datasets (2003 and 2006), it is clear that the wavelength solutions for the PSA and the WCA are different. It was demonstrated that the 2003 PSA dispersion solutions can be used for the 2006 PSA data, obtained with a different COS-to-RASCAL alignment angle, and still meet the specifications of ± 15 km/s (CEI Sec. 4.2.1).

Once in orbit, we will rely on the spectra from the WCA to obtain an absolute wavelength scale. Since the separation between the WCA and the PSA is dependant on the exact angle of the incoming beam (installation uncertainties), we will need to measure this separation once in orbit using a source with well known spectral features. This value will have to be available to the pipeline for proper processing.

The 1σ errors in absolute wavelength determination was measured to be ± 7 km/s for the G185M, with or without geometric correction. It is thus, not necessary to add the extra step of correcting the geometric distortion, but it is necessary to use PSA obtained wavelength solutions for on-orbit science data wavelength determinations.

APPENDIX A: ALL GRATINGS

The results described above were obtained using data from the G185M grating. We present here the results from all the NUV gratings.

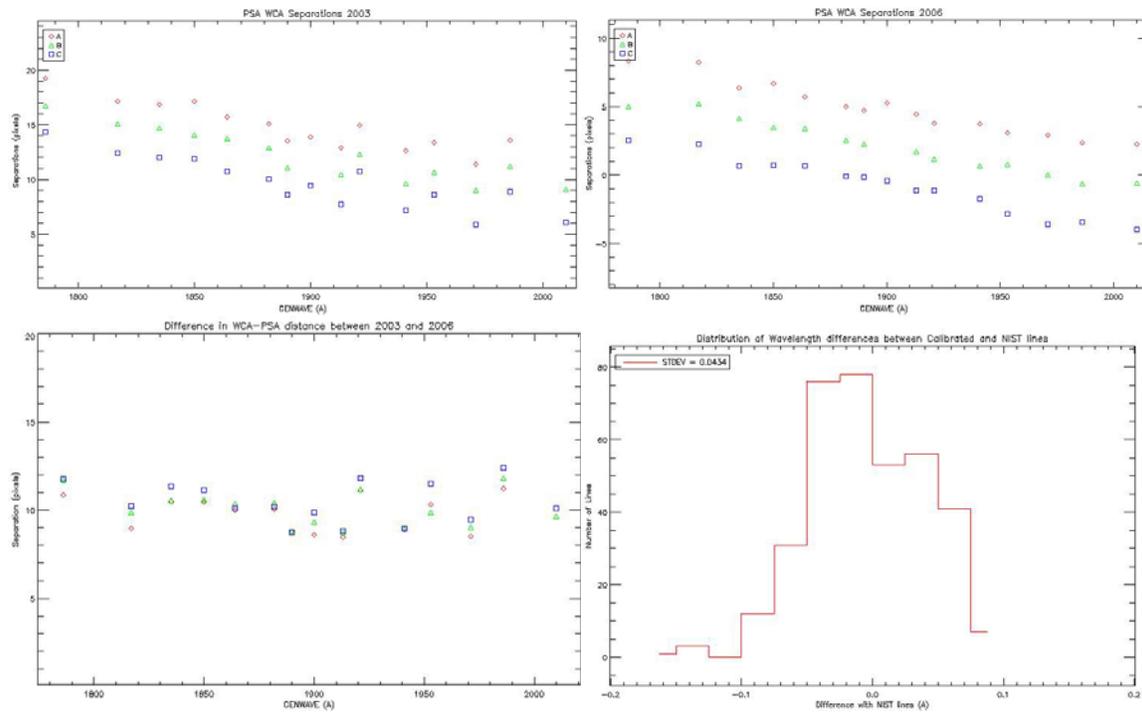


Figure A-1 G185M : a) Separation between the 2003 PSA and WCA spectra, b) separation between the 2006 PSA and WCA spectra, c) differences in separations between 2003 and 2006, d) distribution of residual errors in the wavelengths of identified spectral lines ($\sigma = \pm 7.0$ km/s).

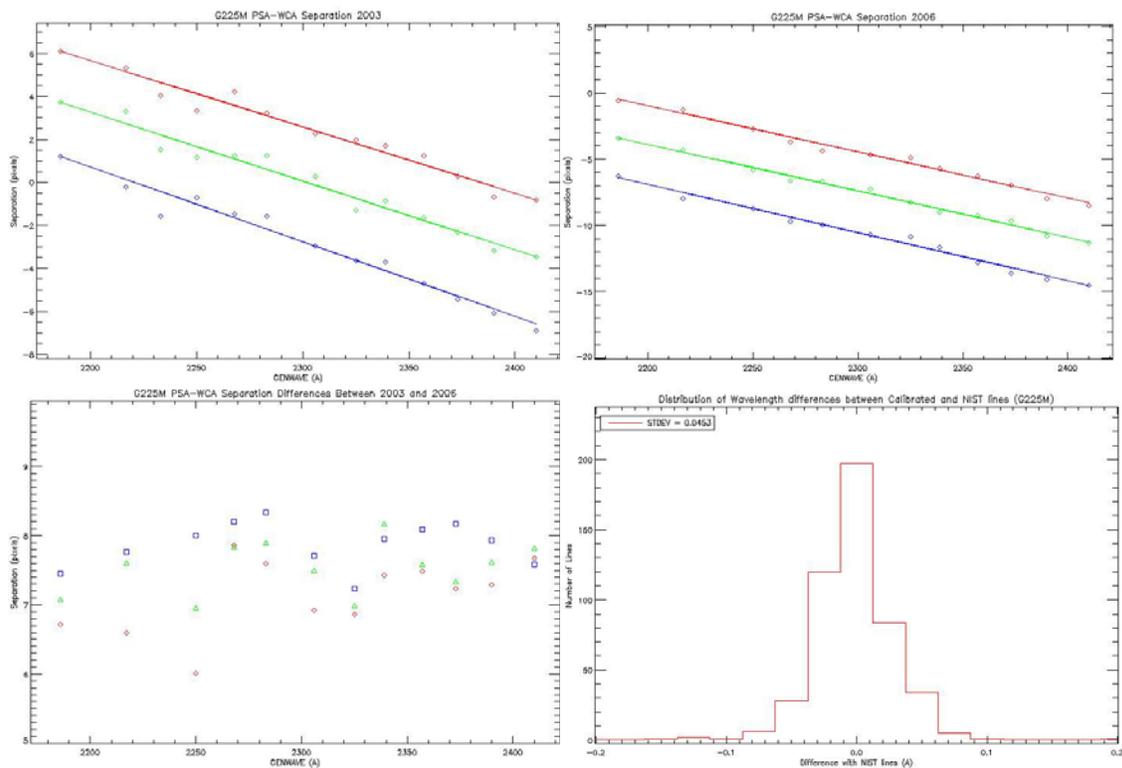


Figure A-2 G225M : a) Separation between the 2003 PSA and WCA spectra, b) separation between the 2006 PSA and WCA spectra, c) differences in separations between 2003 and 2006, d) distribution of residual errors in the wavelengths of identified spectral lines ($\sigma = \pm 6.0$ km/s).

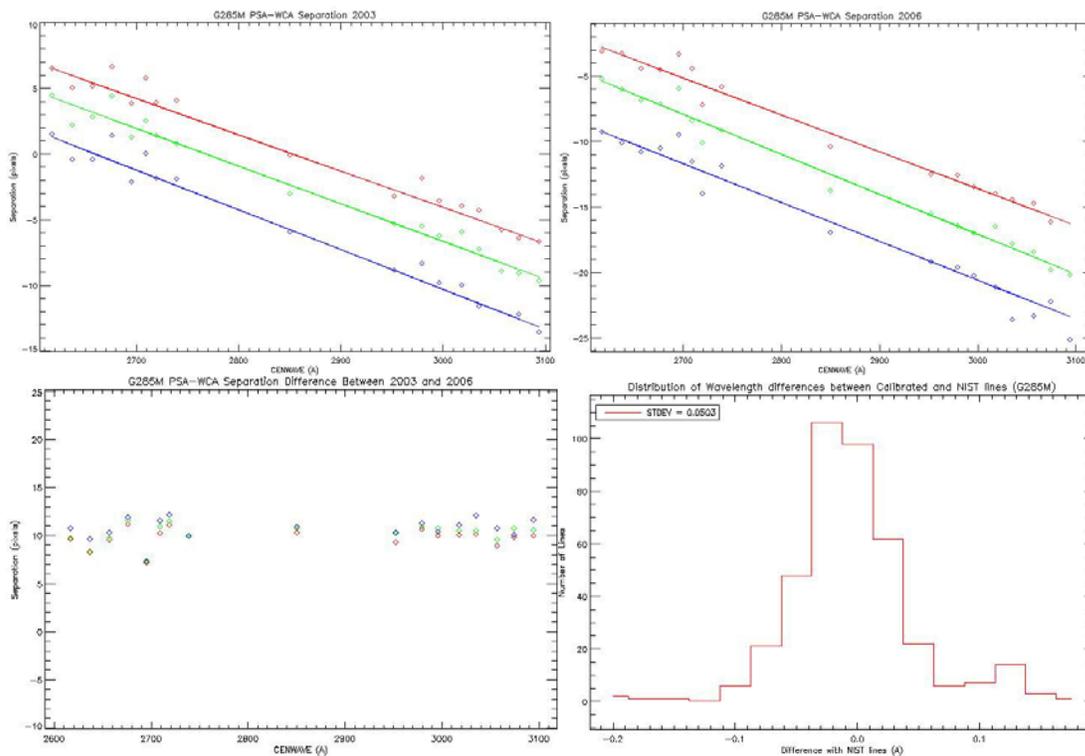


Figure A-3 G285M : a) Separation between the 2003 PSA and WCA spectra, b) separation between the 2006 PSA and WCA spectra, c) differences in separations between 2003 and 2006, d) distribution of residual errors in the wavelengths of identified spectral lines ($\sigma = \pm 5.3$ km/s).

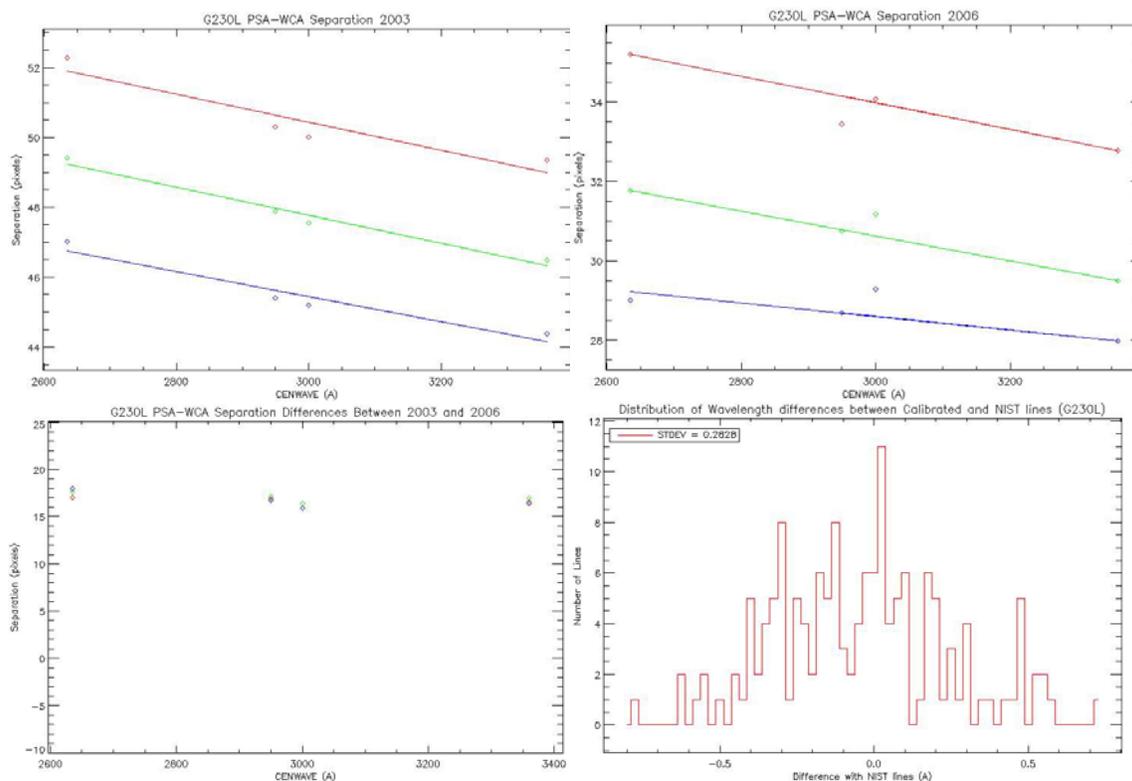


Figure A-4 G230L : a) Separation between the 2003 PSA and WCA spectra, b) separation between the 2006 PSA and WCA spectra, c) differences in separations between 2003 and 2006, d) distribution of residual errors in the wavelengths of identified spectral lines ($\sigma = \pm 40$ km/s). Note that the specifications for the wavelength calibration is ± 175 km/s for the G230L grating.