Wavelength Calibration of the *Cosmic Origins Spectrograph*

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The *Cosmic Origins Spectrograph* onboard the *Hubble Space Telescope*, provides wavelength coverage from the Lyman limit to ~2250 Å with the FUV channel (R = 16,000 - 21,000 with the M gratings and 2100 - 3900 with the L grating), and from 1670 to 3560 Å with the NUV channel (R = 22,000 - 41,000 with the M gratings and 2100 - 3900 with the L grating).

SUMMARY

Wavelength dispersion solutions for the FUV and NUV detectors were derived using data obtained in thermal vacuum 2003, TV03. For each segment (in the FUV) or stripe (in the NUV), dispersion relations were derived for each grating/cenwave setting, independently for the PSA and WCA apertures, using emission lines from a PtNe line lamp. During SMOV, calibration programs 11474 and 11487 were carried out to characterize the wavelength scales of the NUV and FUV detectors, respectively. Science data were obtained through the Primary Science Aperture (PSA), simultaneously with PtNe lamp line data obtained through the Wavelength Calibration Aperture (WCA). These data were partially calibrated with the COS pipeline and then, in conjunction with STIS data of the same target, used to derive offsets between the external (PSA) and internal (WCA) wavelength scales. These offsets are then used to place the dispersion solutions derived from TV03 data in the on-orbit frame of reference.

DATA ANALYSIS - FUV

- Rawtag files for science exposures obtained in program 11487 were partially calibrated by setting all switches to *OMIT* except for *TEMPCORR*, *GEOCORR*, *IGEOCORR*, *DOPPCORR*, and *WAVECORR*, set to *PERFORM*. Update lamp template reference file used (see below).
- *XFULL* and *YFULL* columns extracted for PSA and WCA data, producing 1d spectra, counts vs pixel
- 1-d WCA spectra were cross-correlated with PtNe lamp line list, assigning wavelengths to each of the PtNe emission lines seen in pixel space. Each line has then pixel coordinate $WCA_{SMOV,i}$
- Pixel positions in 1-d PSA spectra ($PSA_{SMOV,i}$), corresponding to the wavelengths of the PtNe emission lines identified in previous step, were identified, by using STIS spectra of the same target as a guide.
- For each grating/cenwave/segment setting this procedure is applied to as many features as possible, so that one can determine $PSA_{SMOV,i}$ - $WCA_{SMOV,i}$ across each segment of FUV detector.
- On-orbit separation between PSA and WCA is then the mean of ($PSA_{SMOV,i}$ - $WCA_{SMOV,i}$).

DATA ANALYSIS - NUV

- Rawtag files for science exposures in program 11474 partially calibrated by setting all switches to *OMIT* except for *DOPPCORR* and *WAVECORR* which were set to *PERFORM*.
- Analysis similar to the one performed for the FUV data obtained in program 11487.

TABLE 1 AND TABLE 2 CONTAIN THE NUV AND FUV MEASUREMENTS, RESPECTIVELY.

LAMP TEMPLATE REFERENCE FILES

- Programs 11488 (FUV) and 11475 (NUV) obtained internal wavelength calibration spectra using the default PtNe line lamp (lamp 1) at all central wavelengths of all gratings, for all FP-POS.
- Typical exposures times were 120 sec, with some NUV exposures being 150 sec. In order to allow the mechanism drift to settle after a grating motion, a 1800 sec exposure, containing multiple flashes of the lamp was taken at the beginning of each visit.
- The wavecal exposures are used to update the FUV and NUV lamp template reference files (*lamp.fits). To assess the impact of mechanism drift in the wavecal exposures, each exposure was divided in 30 sec time slices, and each time slice was cross-correlated with the first 30 sec of the exposure.
- Maximum drift was 1.3 pix for the FUV exposures (with most within 0.5 pix) and 0.9 pix for the NUV exposures (with most below 0.3 pix). For both the FUV and NUV, these values are much smaller than a resolution element (6 and 3 pix, respectively) and so no drift correction was applied.

WAVELENGTH CALIBRATION IN CalCOS

- CalCOS corrects the pixel positions of the science data for mechanism drift by cross-correlating WCA data (TAGFLASH or AUTO or GO-WAVECAL) with the lamp template corresponding to the same setting. Column *XFULL* in *CORRTAG* file contains this and other corrections.
- The COS pipeline computes the wavelength from the *XFULL* pixel coordinate as:

$XPRIME = XFULL + d_{PSA}$ where:

$d_{PSA} = d_{TV03} - d$; $\quad d_{TV03} = PSA_{TV03} - WCA_{TV03}$; $\quad d = PSA_{SMOV} - WCA_{SMOV} - (WCA_{TV03} - WCA_{SMOV})$

Both d_{TV03} and d are columns in the wavelength dispersion reference file

Wavelengths are then computed from:

$\lambda = a_0 + a_1 \cdot XPRIME + a_2 \cdot XPRIME^2$ a_0, a_1, and a_2 are the dispersion coefficients derived from TV03 data.

Figure 1 below illustrates the relationships between the different quantities described above.

Figure 1: Relationships between the wavecal (WCA) and science (PSA) spectra in TV03 and SMOV

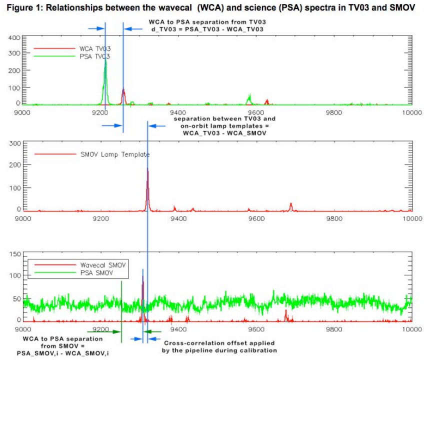

TABLE 1: FUV OFFSETS DERIVED FROM PROGRAM 11487

Grating	Cenwave	Segment	Exposure	$PSA_{SMOV} - WCA_{SMOV}$ (pix)	$WCA_{TV03} - WCA_{SMOV}$ (pix)	d (pix)
G130M	1291	FUVA	labp73giq	−43.9500	545.549	-589.49900
		FUVB	labp73giq	−43.9100	539.081	-582.99100
	1300	FUVA	labp73gkq	−45.1250	497.598	-542.72300
		FUVB	labp73gkq	−43.1571	493.395	-536.55210
	1309	FUVA	labp50alq, labp73gg	−43.1108	460.714	-503.82480
		FUVB	labp50alq, labp73gg	−42.9489	452.028	-494.97690
	1318	FUVA	labp73gmq	−42.0080	480.279	-522.28700
		FUVB	labp73gmq	−42.9312	467.639	-510.57020
	1327	FUVA	labp73goq	−41.8940	449.035	-490.92900
		FUVB	labp73goq	−43.9300	431.948	-475.87800
G160M	1577	FUVA	labp73gqq	−44.1720	-4.49852	-39.673480
		FUVB	labp73gqq	−43.1140	-4.19682	-38.917180
	1589	FUVA	labp73gsq	−43.7133	-21.8603	-21.853000
		FUVB	labp73gsq	−41.4575	-23.1098	-18.347700
	1600	FUVA	labp73geq	−41.8280	-27.4868	-14.341200
		FUVB	labp73geq	−40.8389	-31.9993	-8.8396000
	1611	FUVA	labp73guq	−45.4032	-44.3193	-1.0839000
		FUVB	labp73guq	−36.9424	-53.2402	16.297800
	1623	FUVA	labp73gwq	−45.4716	-48.4831	3.0115000
		FUVB	labp73gwq	−43.5691	-63.0932	19.524100
G140L	1105	FUVA	labp73hhq	−44.4749	-42.3273	-2.1476000
	1230	FUVA	labp50arq, labp73h8q	−45.8595	-66.0997	20.240200
		FUVB	-	−45.8595	-66.0997	20.240200

TABLE 1: Offsets for G140L/1230/FUVB are the same as those for G140L/1230/FUVA, since the PtNe lamp does not produce counts at these short wavelengths.

TABLE 2: NUV OFFSETS DERIVED FROM PROGRAM 11474

Grating	Cenwave	Stripe A (pixel)	Stripe B (pixel)	Stripe C (pixel)	d (pixel)	Notes
G225M	2186	no overlap, 35.412	no overlap, 35.874	10.296, 36.094	··· , ··· , -25.798	Vis 01
	2217	no overlap, 33.223	no overlap, 33.591	11.910, 33.783	··· , ··· , -21.873	Vis 01
	2233	no overlap, 33.352	no overlap, 33.733	12.379, 33.738	··· , ··· , -21.359	Vis 01
	2250	no overlap, 34.934	no overlap, 35.437	11.607, 35.676	··· , ··· , -24.069	Vis 01
	2268	no overlap, 32.670	9.358, 33.052	9.817, 33.141	··· , -23.694, -23.324	Vis 01
	2283	no overlap, 29.375	9.817, 29.681	12.990, 29.885	··· , -19.864, -16.895	Vis 01
	2306	no overlap, 29.905	11.108, 30.331	14.653, 30.274	··· , -19.223, -15.621	Vis 01
	2325	no overlap, 29.952	11.651, 30.128	14.831, 30.566	··· , -18.477, -15.735	Vis 01
	2339	no overlap, 33.193	12.520, 33.548	13.989, 33.778	··· , -21.028, -19.789	Vis 01
	2357	10.491, 30.857	12.085, 31.175	15.542, 31.462	-20.366, -19.090, -15.920	Vis 01
	2373	9.517, 32.645	12.897, 33.283	16.734, 33.267	-23.128, -20.386, -16.533	Vis 01
	2390	10.172, 32.510	12.661, 33.024	16.801, 33.141	-22.338, -20.363, -16.340	Vis 01
	2410	11.335, 29.070	13.799, 29.420	18.073, 29.467	-17.735, -15.621, -11.394	Vis 01
G285M	2617	3.297, 33.766	5.260, 33.960	9.754, 34.344	-30.469, -28.700, -24.590	Vis 01
	2637	3.948, 35.125	6.405, 35.652	11.178, 35.883	-31.177, -29.247, -24.705	Vis 01
	2657	4.208, 30.183	7.395, 30.546	8.697, 30.664	-25.975, -23.151, -21.967	Vis 01
	2676	4.368, 33.161	6.815, 33.391	10.653, 33.871	-28.793, -26.576, -23.218	Vis 01
	2695	5.019, -106.233	8.827, -108.190	10.631, -110.788	111.252, 117.017, 121.419	Vis 01
	2709	4.913, 34.826	9.043, 35.237	11.110, 35.488	-29.913, -26.194, -24.378	Vis 01
	2719	5.460, 40.373	8.355, 40.900	12.177, 41.262	-34.913, -32.545, -29.083	Vis 02
	2739	4.892, 38.412	9.163, 38.925	9.502, 39.545	-33.520, -29.762, -30.043	Vis 02
	2850	9.286, 35.221	13.093, 35.605	17.505, 35.995	-25.935, -22.512, -18.490	Vis 01
	2952	13.848, 35.923	13.544, 36.721	19.516, 37.043	-22.075, -23.177, -17.527	Vis 02
	2979	-4.795, 35.162	-2.431, 35.521	-0.108, 36.144	-39.957, -37.952, -36.252	Vis01
	2996	13.177, 36.118	16.058, 36.722	no wavecal, 36.892	-22.941, -20.664, ···	Vis 02
	3018	12.859, 36.425	16.533, 37.312	20.399, 37.645	-23.566, -20.779, -17.246	Vis 02
	3035	-4.186, 36.121	-2.043, 36.645	no overlap, 37.040	-40.307, -38.688, ···	Vis 01
	3057	16.881, 38.474	19.515, 39.584	no wavecal, 40.594	-21.593, -20.069, ···	Vis 01
	3074	16.794, 37.095	20.115, 37.575	no wavecal, 38.455	-20.301, -17.460, ···	Vis 01
	3094	17.264, 37.757	19.944, 38.475	no overlap, 39.149	-20.493, -18.531, ···	Vis 01
G230L	2635	low S/N, -1.81	-40.284, -2.282	low S/N, -3.149	··· , -38.002, ···	Vis 02
	2950	no overlap, 3.083	-38.334, 2.703	low S/N, 1.914	··· , -41.037, ···	Vis 02
	3000	no overlap, 4.576	-39.609, 4.235	low S/N, 3.662	··· , -43.844 , ···	Vis 02
	3360	-40.715, -2.725	no overlap, -3.127	no wavecal, -4.023	-37.990, ··· , ···	Vis 02

TABLE 2: The first number reported in columns 3-5 is the mean of ($PSA_{SMOV,i}$ - $WCA_{SMOV,i}$) for each stripe, the second number is WCA_{TV03}-WCA_{SMOV} for each stripe as well. Entries labeled no overlap indicate that the on-orbit separation between PSA and WCA could not be measured because COS and STIS data do not overlap. Columns marked no wavecal indicate cases for which S/N of wavecal data is too low; entries marled low S/N indicate cases for which S/N of science data is too low.

APPLICATION OF UPDATED WAVELENGTH SCALES TO COS/FUV AND COS/NUV DATA

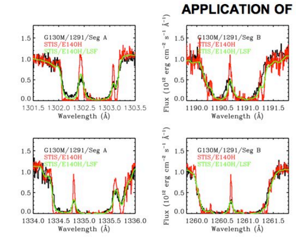

Figure 2: Comparison between wavelength calibrated COS G130M/1291 data for SK 155 (black; program 11489, FP=3) and STIS/E140H data for the same target (red). STIS data convolved with the LSF appropriate to the wavelengths and settings displayed are also shown (green). For seg A the COS and STIS wavelengths are in good agreement; for seg B 1190 Å the COS wavelengths are under-predicted by ~4 pix while at 1260 Å they are under-predicted by ~2 pix.

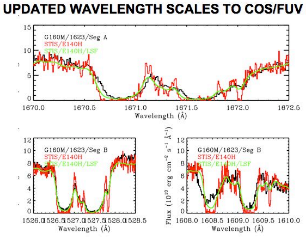

Figure 3: Comparison between wavelength calibrated COS G160M/1623 data for SK 155 (black; program 11489, FP=1,2,3,4) and STIS/E140H data for the same target (red). STIS data convolved with the LSF appropriate to the wavelengths and settings displayed are also shown (green). For seg A the COS wavelengths are over-predicted by ~3pix; for seg B/1526 Å the COS wavelengths are in good agreement with those from STIS, while at 1609 Å they are under-predicted by ~3 pix.

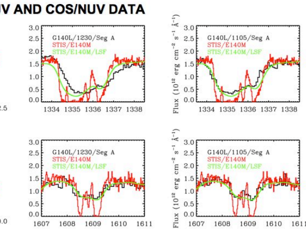

Figure 4: Comparison between wavelength calibrated COS G140L/1230 (left panel) and G140L/1105 (right panel) data for NGC 330-B37 (black, program 11487, FP=3) and STIS E140M data for the same target (red). STIS data convolved with the LSF appropriate to the wavelengths and settings displayed are also shown. For G140L/1230 the COS wavelengths are over-predicted by ~3pix for 1335 Å and under-predicted by ~1 pix for 1609 Å. For G140L/1105 the COS wavelengths are under-predicted by ~2 pix for 1335 Å and they agree well with those of STIS at 1609 Å.

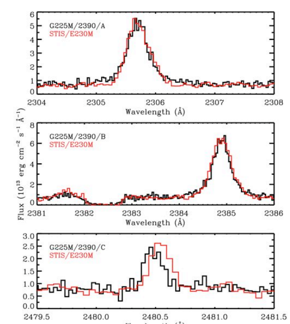

Figure 5: Comparison between wavelength calibrated COS G225M/2390 data for AG DRA (black; program 11477, FP=3) and STIS/E230M data for the same target (red). There is good agreement between the COS and STIS wavelengths for stripes A and B, for stripe C the COS wavelengths are under-predicted by 2 pix.

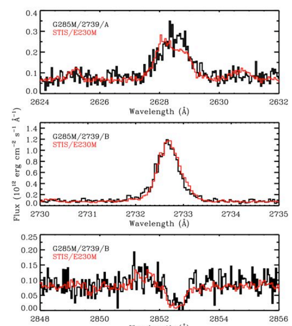

Figure 6: Comparison between wavelength calibrated COS G285M/2739 data for AG DRA (black; program 11477, FP=3) and STIS/E230M data for the same target (red). For both stripes A and C the COS wavelengths are over-predicted by ~1 pix, while for stripe B, the COS wavelengths are under-predicted by the same amount.

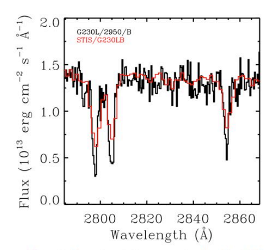

Figure 7: Comparison between wavelength calibrated COS G230L/2950/B data for AzV 18 (black; program 11472, FP=3) and STIS/G230LB data for the same target (red). The COS wavelengths are under-predicted by 1-2 pix.

RESULTS & FUTURE WORK

Wavelength scales for NUV/G185M have not been updated yet as the target observed for this purpose (Feige 48) requires additional work to correct the spectra for the orbital motion. The updated wavelength scales have been applied to a limited number of datasets both in the FUV and NUV. However, all the cases presented here seem to indicate that the accuracy of the wavelength scales is within the specifications defined in Table 3.

We have two Cycle 17 calibration programs in place (11997 for FUV and 11900 for NUV) to monitor the offsets between the PSA and WCA apertures. In addition we will analyze data obtained in SMOV, GTO, and GO programs that will allow us to further refine our evaluation of the wavelength accuracies.

TABLE 3: COS SPECIFICATONS FOR WAVELENGTH ACCURACIES

Grating	Error Goal (1σ)		Internal error (1σ)
	km s^{-1}	pixels	pixels
G130M	15	5.7-7.5	3.0-4.0
G160M	15	5.8-7.2	3.1-3.8
G140L	150	7.5-12.5	4.0-6.6
G185M	15	7.2-10.0	1.2-1.7
G225M	15	9.7-13.3	1.6-2.3
G285M	15	9.7-14.7	1.6-2.6
G230L	175	8.3-15.5	1.4-2.6

The internal error includes the accuracy of the wavelength scale, the dispersion relation, aperture offsets, distortions and drifts. The error goal includes contributions from external sources, which are dominated by target mis-centering in the aperture. Error goal given per exposure.

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