In-Flight FOS Wavelength Calibration — Template Spectra

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Abstract

In August and October 1990 FOS spectra of the internal Pt-Cr-Ne calibration lamps were obtained with the red and blue detectors respectively, through a set of paired apertures (the 0.1" and 0.25") and through the centered 0.3" circular aperture. These spectra give the initial dispersion solutions for the FOS gratings and prisms, and they will serve as reference template spectra for future calibrations. The wavelength solutions show shifts of less than two diodes from pre-flight calibrations on the blue side and less than three diodes on the red side. Root-mean-square residuals are typical of those found from the ground calibration data.

I. Introduction

The first in-flight data for the calibration of the FOS wavelength scale were obtained under proposal 2099, "Wavelength Calibration — Template Spectra", during the second half of the orbital verification phase (OV/2) of Hubble Space Telescope operations. Exposures of the internal Pt-Cr-Ne lamps were made with each detector/dispersing element combination. One set of exposures used the 0.1" and the 0.25" paired apertures, and another used the centered 0.3" circular aperture. In each case we used the smallest aperture which would give adequate signal-to-noise (S/N) ratios without excessive integration time. In addition to providing the initial in-flight wavelength calibration of the FOS, these data serve as reference template spectra for future wavelength calibrations of other detector/disperser/aperture combinations or for individual observations of astrophysical targets.

II. The Calibration Data

The individual observations and the root filenames for the resulting data sets from both the blue and red side calibration sequences are summarized in Table 1. Spectra through the red side of the FOS were obtained on 19 August 1990. All spectra on the red side were well exposed. Data for the blue side of the FOS were obtained on 23 October 1990. The G400H spectrum through the 0.3" aperture (Y0AN0302T) and the short (2 s) prism exposure through the 0.3" aperture (Y0AN0306T) on the blue side had several pixels with saturated counting rates. All other spectra were well exposed.

III. Data Reduction and Analysis

Most data that had been calibrated by the RSDP system were suitable as-is for analysis of the wavelength calibration. The calibrated output files *.C5H,*.C5D are preferred for wavelength calibration since these have been corrected for dead diodes, converted to count rates, corrected for linearity, and flat-fielded. This gives the best estimate of the true line profiles and hence the most reproducible line centers. The RSDP system automatically assumes that the upper aperture in paired-aperture spectra are sky background that should be subtracted, however, so these output files are not suitable for wavelength calibration of paired apertures. All paired-aperture spectra were re-processed off-line using the *calfos* task in IRAF/STSDAS with the background-subtraction disabled. This produces appropriately corrected spectra for only the *lower* aperture of the pair, however. For the upper apertures we used the *.C4H,*.C4D files. These files have only been converted to count rates and corrected for dead diodes. Additional special cases required re-processing of individual spectra using *calfos*. These included several red spectra with wrap-around problems and the saturated blue spectra.

A bug in the RSDP processing software introduced wrap-arounds into several of the red spectra from the pipeline processing. These problems were corrected by re-reducing the data with the *calfos* task in IRAF/STSDAS, which did not have the same bug. This problem was fixed in the RSDP system before the blue side data were obtained.

Saturated pixels are replaced by zeroes in the RSDP processing, so the two saturated blue spectra were re-reduced using *calfos* with a modified paired-pulse-correction table (CCG2). The table listed in the file header was copied from SCIVAX, and the RSAT entry was edited with the *tedit* task in the TTOOLS package of STSDAS to a value greater than the rates seen in the two saturated spectra to prevent them from being zeroed out in the linearity correction process.

We obtained dispersion solutions using Don Lindler's IRAF/STSDAS implementation of the Sirk and Bohlin algorithms described in CAL/FOS-026. The selected lines tabulated by Sirk and Bohlin were identified in the calibration spectra and centroided by the task *linefind* in the FOS package of STSDAS using the cross-correlation algorithm described in CAL/FOS-026. We used the same peak-finding kernel for the cross-correlation, a three-point triangle with relative weights 0.8, 1.0, 0.8, as used by Sirk and Bohlin. Line list tables were prepared for each detector and grating based on the last ground calibration results (see Kriss, Blair, and Davidsen 1988). The ASCII line lists were converted to SDAS tables using the *tcreate* task in the TTOOLS package.

Using the task *dispfity*, also in the FOS package of STSDAS, the diffraction grating spectra were fit with a cubic polynomial of the form

$$\lambda = A + Bx + Cx^2 + Dx^3 \ ,$$

where x is the diode number and λ is the corresponding wavelength. Uniform weighting for each line was used in the fit. The resulting dispersion solutions for the diffraction gratings are presented in Table 2.

The prism spectra were also fit by *dispfity* with the dispersion formula given in CAL/FOS-026:

$$\lambda = A_o + \frac{A_1}{(x-X_o)} + \frac{A_2}{(x-X_o)^2} + \frac{A_3}{(x-X_o)^3} + \frac{A_4}{(x-X_o)^4} \ .$$

Lines were weighted by the reciprocal of the local dispersion because this preserves the uniformity of the errors in diode space. The best fit dispersion solutions for the red and blue prism spectra are also given in Table 2.

Because of the form used for the prism dispersion relations, physically reasonable wavelengths are obtained over the full range of diodes only if $X_o < 0$ on the blue side, and $X_o > 516$ on the red side. This condition is satisfied for the blue prism solutions, but it is not for the red. We attempted to force X_o to be greater than 516, but could not obtain dispersion relations with reasonable residuals. The physical interpretation of the best fitting X_o value is that this represents the point of zero deviation of light by the prism on the diode array, hence wavelengths approaching infinity. Any photons detected in diodes beyond X_o must be scattered light from shorter wavelengths. The best solution to the problem of unphysical wavelengths is to change the algorithm which is used to generate the wavelength array in RSDP and *calfos*, *e.g.*, set all wavelengths in diodes $> X_o$ to the wavelength of the last pixel just less than X_o.

The root-mean-square residuals from the wavelength solutions are typical of those seen in the pre-flight calibrations. The gratings generally have rms residuals < 0.05 diodes; exceptions are the blue side G130H and G650L solutions with rms residuals of ~0.1 diodes. These spectra suffer from a paucity of strong, isolated lines. As usual, the badly blended prism spectra have residuals of 0.1 - 0.3 diodes. Typical residuals from the fits are shown in Figures 1a-1d. We show a typical good fit for grating G400H on the blue side in Figure 1a, residuals from fits to G130H and G650L on the blue side in Figures 1b and 1c, respectively, and a fit to the red prism spectrum in Figure 1d. None of the residuals show any systematic trends.

In general, linear fits ($\lambda = a + bx$) for the grating dispersion solutions are not adequate, yet they provide a quick estimate of wavelength accurate to a few tenths of a diode. The wavelength ranges covered by each grating and the best linear fits are given in Table 3. While previous calibrations indicated that linear fits were acceptable for the G150L grating, a cubic fit to the in-flight data has significantly lower residuals. As noted in CAL/FOS-054, these differences may be due to the lack of observed lines below 1900 Å in ambient calibration data.

IV. Preparing Data for PDB Submission

To assemble a new table of wavelength coefficients for submission to the PDB, we went through a rather tortuous process. The wavelength coefficient table (CYCCS6) has a total of 768 entries — one for each detector, aperture, disperser, and polarization mode combination. To minimize errors, all modifications to the table were made with software tasks which used the new calibration results and the old table as inputs, and produced an updated table in a codified way.

The *dispfity* task produces an SDAS table containing the wavelength coefficients. Each table file was named using a convention which included the root filename and a "u" or an "l" to identify the solution as an upper or lower aperture solution as appropriate. These table files were dumped in ASCII format to a file with the same root name and a ".dat" extension. These separate files were concatenated into a single file containing all new wavelength solutions with their associated instrument parameters (detector, aperture, disperser, and polarization mode).

To update the CYCCS6 table, a C program first read the new coefficients and identifying information into a data structure. The old CYCCS6 table was then read an entry at a time, and the following strategy was used to update the coefficients for that entry —

- If a new wavelength solution exists which has matching detector, disperser, and aperture parameters, those new coefficients are used for the new table.
- If only the detector and disperser parameters match and the aperture does not, new solutions which match the UPPER, LOWER, or SINGLE aperture modifiers are used as appropriate.
- Only the detector, disperser, and aperture parameters are used to determine the coefficients, independent of polarization mode. Each polarization mode entry with identical detector, disperser, and aperture parameters is updated with the same set of coefficients.

The updated ASCII output file is then converted to the SDAS table format documented in Evans (1990) for submission to the PDB using the *tcreate* task in the TTOOLS package of STSDAS. The table was placed in the FOS directory on SCIVAX, and Ian Evans proceeded with the submission.

IV. Conclusions

Both the blue and red FOS detectors show only small shifts from the last ground wavelength calibration in August 1988. Offsets of up to two diodes are seen on the blue side, and offsets of up to three diodes are seen on the red side. We note that *none* of the data have had any corrections applied for the Geomagnetically-induced Image Motion Problem (GIMP; see CAL/FOS-066, Junkarrinen *et al.*, 1990), and some of the more extreme offsets on the red side may be GIMP related. Once a strategy for making GIMP corrections has been devised and implemented, these data should be corrected, and new wavelength solutions should be obtained which are applicable to standard GIMP-corrected spectra.

References

Sirk, M., and Bohlin, R. 1986. CAL/FOS-026, *FOS Wavelength Calibration.*

Kriss, G. A., Blair, W. P., and Davidsen, A. F. 1988. CAL/FOS-054, *Revised FOS Wavelength Calibration.*

Evans, I. 1990. *A Cookbook for the Delivery of PDB, IMDB, and CDBS Data.*

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TABLE 1
WAVELENGTH TEMPLATE SPECTRA BASIC INFORMATION

FILENAME	DET	DISP	APERTURE	DATE	TIME	EXPOSURE(s)
y0an0401	RED	G650L	0.1-PAIR	19AUG90	07:13EDT	48.0
y0an0402	RED	G780H	0.1-PAIR	19AUG90	07:17EDT	48.0
y0an0403	RED	G270H	0.1-PAIR	19AUG90	07:20EDT	144.0
y0an0404	RED	G570H	0.1-PAIR	19AUG90	07:26EDT	40.0
y0an0405	RED	G400H	0.1-PAIR	19AUG90	07:30EDT	32.0
y0an0501	RED	G160L	0.25-PAIR	19AUG90	08:55EDT	120.0
y0an0502	RED	PRISM	0.25-PAIR	19AUG90	09:01EDT	100.0
y0an0503	RED	PRISM	0.25-PAIR	19AUG90	09:05EDT	8.0
y0an0504	RED	G190H	0.25-PAIR	19AUG90	09:08EDT	120.0
y0an0601	RED	G400H	0.3	19AUG90	10:38EDT	4.0
y0an0602	RED	G160L	0.3	19AUG90	10:41EDT	46.7
y0an0603	RED	G650L	0.3	19AUG90	10:44EDT	6.0
y0an0604	RED	PRISM	0.3	19AUG90	10:47EDT	44.0
y0an0605	RED	PRISM	0.3	19AUG90	10:50EDT	4.0
y0an0606	RED	G780H	0.3	19AUG90	10:53EDT	8.0
y0an0607	RED	G270H	0.3	19AUG90	10:56EDT	10.0
y0an0608	RED	G190H	0.3	19AUG90	10:59EDT	46.7
y0an0609	RED	G570H	0.3	19AUG90	11:02EDT	6.0
y0an0101	BLUE	G400H	0.1-PAIR	23OCT90	19:20EDT	16.0
y0an0102	BLUE	G650L	0.1-PAIR	23OCT90	19:24EDT	28.0
y0an0103	BLUE	PRISM	0.1-PAIR	23OCT90	19:27EDT	8.0
y0an0104	BLUE	PRISM	0.1-PAIR	23OCT90	19:30EDT	80.0
y0an0105	BLUE	G270H	0.1-PAIR	23OCT90	19:34EDT	60.0
y0an0201	BLUE	G570H	0.1-PAIR	23OCT90	20:51EDT	36.0
y0an0202	BLUE	G190H	0.25-PAIR	23OCT90	20:56EDT	56.0
y0an0203	BLUE	G130H	0.25-PAIR	23OCT90	21:00EDT	320.0
y0an0204	BLUE	G160L	0.25-PAIR	23OCT90	21:09EDT	56.0
y0an0301	BLUE	G130H	0.3	23OCT90	22:33EDT	150.0
y0an0302	BLUE	G400H	0.3	23OCT90	22:33EDT	4.0
y0an0303	BLUE	G150L	0.3	23OCT90	22:38EDT	24.0
y0an0304	BLUE	G650L	0.3	23OCT90	22:44EDT	4.0
y0an0305	BLUE	PRISM	0.3	23OCT90	22:46EDT	4.0
y0an0306	BLUE	PRISM	0.3	23OCT90	22:49EDT	2.0
y0an0307	BLUE	G270H	0.3	23OCT90	22:52EDT	4.0
y0an0308	BLUE	G190H	0.3	23OCT90	22:55EDT	24.0
y0an0309	BLUE	G570H	0.3	23OCT90	22:58EDT	16.0

TABLE 2
WAVELENGTH COEFFICIENTS FOR ON ORBIT TEMPLATE SPECTRA

DET	DISP	APERTURE	COEFF1	COEFF2	COEFF3	COEFF4	COEFF5	COEFF6	RMS (DIODES)
RED	G650L	0.1-PAIR-L	8721.62	-24.78164	1.490979e-03	-2.756626e-06	0.000000e+00	0.000000e+00	0.027
RED	G650L	0.1-PAIR-U	8722.39	-24.77306	1.378315e-03	-2.540496e-06	0.000000e+00	0.000000e+00	0.013
RED	G780H	0.1-PAIR-L	9221.78	-5.705855	1.031783e-05	-6.626205e-08	0.000000e+00	0.000000e+00	0.045
RED	G780H	0.1-PAIR-U	9221.42	-5.700305	-8.940143e-06	-4.725990e-08	0.000000e+00	0.000000e+00	0.041
RED	G270H	0.1-PAIR-L	3278.40	-2.045111	2.167873e-05	-4.452183e-08	0.000000e+00	0.000000e+00	0.033
RED	G270H	0.1-PAIR-U	3278.57	-2.045922	2.440367e-05	-4.773611e-08	0.000000e+00	0.000000e+00	0.040
RED	G570H	0.1-PAIR-L	6819.45	-4.359225	5.144460e-05	-1.042818e-07	0.000000e+00	0.000000e+00	0.031
RED	G570H	0.1-PAIR-U	6819.54	-4.357716	4.298524e-05	-9.589921e-08	0.000000e+00	0.000000e+00	0.036
RED	G400H	0.1-PAIR-L	4783.71	-2.993945	2.266364e-05	-5.740824e-08	0.000000e+00	0.000000e+00	0.031
RED	G400H	0.1-PAIR-U	4783.92	-2.995708	2.914448e-05	-6.494363e-08	0.000000e+00	0.000000e+00	0.034
RED	G160L	0.25-PAIR-L	2431.31	-7.018783	3.546548e-03	-2.039457e-05	0.000000e+00	0.000000e+00	0.027
RED	G160L	0.25-PAIR-U	2431.53	-6.992240	2.952427e-03	-1.697944e-05	0.000000e+00	0.000000e+00	0.030
RED	PRISM	0.25-PAIR-L	1148.33	-1.360773e+05	-1.815413e+06	-3.435690e+07	-2.131851e+08	5.096669e+02	0.187
RED	PRISM	0.25-PAIR-U	1134.56	-1.407849e+05	-1.844615e+06	-4.687603e+07	-2.967242e+08	5.134487e+02	0.096
RED	G190H	0.25-PAIR-L	2312.40	-1.432992	8.787011e-06	-2.318103e-08	0.000000e+00	0.000000e+00	0.029
RED	G190H	0.25-PAIR-U	2312.51	-1.433915	1.238694e-05	-2.775356e-08	0.000000e+00	0.000000e+00	0.025
RED	G400H	0.3	4784.07	-2.994351	2.263009e-05	-5.606696e-08	0.000000e+00	0.000000e+00	0.027
RED	G160L	0.3	2430.05	-6.974074	2.769016e-03	-1.632700e-05	0.000000e+00	0.000000e+00	0.037
RED	G650L	0.3	8729.30	-24.77257	1.349881e-03	-2.344068e-06	0.000000e+00	0.000000e+00	0.027
RED	PRISM	0.3	1138.21	-1.384317e+05	-1.945428e+06	-3.828702e+07	-2.439737e+08	5.099755e+02	0.213
RED	G780H	0.3	9218.52	-5.681499	-6.678174e-05	1.292135e-08	0.000000e+00	0.000000e+00	0.052
RED	G270H	0.3	3278.24	-2.044918	2.154916e-05	-4.378742e-08	0.000000e+00	0.000000e+00	0.032
RED	G190H	0.3	2312.38	-1.433080	9.038057e-06	-2.247756e-08	0.000000e+00	0.000000e+00	0.026
RED	G570H	0.3	6819.57	-4.361619	6.679705e-05	-1.214717e-07	0.000000e+00	0.000000e+00	0.030
BLUE	G400H	0.1-PAIR-L	3240.55	3.075582	4.591502e-05	-1.149314e-07	0.000000e+00	0.000000e+00	0.041
BLUE	G400H	0.1-PAIR-U	3240.39	3.074823	4.655872e-05	-1.155243e-07	0.000000e+00	0.000000e+00	0.053
BLUE	G650L	0.1-PAIR-L	-3913.95	24.503618	2.750667e-03	-3.177840e-06	0.000000e+00	0.000000e+00	0.115
BLUE	G650L	0.1-PAIR-U	-3878.87	24.080263	4.237934e-03	-4.808809e-06	0.000000e+00	0.000000e+00	0.103
BLUE	PRISM	0.1-PAIR-L	955.41	193404.278400	-2.481863e+06	7.466010e+06	1.821168e+10	-2.651840e+01	0.253
BLUE	PRISM	0.1-PAIR-U	1188.29	113546.636100	4.385455e+06	-2.455215e+08	8.889562e+09	-1.447873e+01	0.175
BLUE	G270H	0.1-PAIR-L	2222.20	2.097408	3.926563e-05	-9.146773e-08	0.000000e+00	0.000000e+00	0.047
BLUE	G270H	0.1-PAIR-U	2222.09	2.096966	4.045417e-05	-9.339767e-08	0.000000e+00	0.000000e+00	0.040
BLUE	G570H	0.1-PAIR-L	4574.73	4.477862	4.878077e-05	-1.473024e-07	0.000000e+00	0.000000e+00	0.043
BLUE	G570H	0.1-PAIR-U	4574.67	4.472214	8.674111e-05	-2.223127e-07	0.000000e+00	0.000000e+00	0.045
BLUE	G190H	0.25-PAIR-L	1573.39	1.468251	3.939659e-05	-7.708150e-08	0.000000e+00	0.000000e+00	0.021
BLUE	G190H	0.25-PAIR-U	1573.31	1.468868	3.643564e-05	-7.459450e-08	0.000000e+00	0.000000e+00	0.021
BLUE	G130H	0.25-PAIR-L	1088.35	0.994298	6.239162e-05	-8.690269e-08	0.000000e+00	0.000000e+00	0.117
BLUE	G130H	0.25-PAIR-U	1089.40	0.985630	8.483852e-05	-1.067738e-07	0.000000e+00	0.000000e+00	0.152
BLUE	G160L	0.25-PAIR-L	-1078.28	6.855216	5.000274e-04	-5.743333e-07	0.000000e+00	0.000000e+00	0.066
BLUE	G160L	0.25-PAIR-U	-1047.45	6.640521	9.815462e-04	-9.307498e-07	0.000000e+00	0.000000e+00	0.069
BLUE	G130H	0.3	1087.58	1.002487	3.520392e-05	-5.914022e-08	0.000000e+00	0.000000e+00	0.082
BLUE	G400H	0.3	3240.43	3.074753	4.915836e-05	-1.202550e-07	0.000000e+00	0.000000e+00	0.034
BLUE	G150L	0.3	-898.61	5.612260	3.312147e-03	-2.672266e-06	0.000000e+00	0.000000e+00	0.083
BLUE	G650L	0.3	-3937.42	24.793402	1.935360e-03	-2.498303e-06	0.000000e+00	0.000000e+00	0.169
BLUE	PRISM	0.3	1081.57	136416.520000	4.792724e+06	-4.161665e+08	1.860369e+10	-1.953349e+01	0.279
BLUE	G270H	0.3	2221.65	2.097014	4.047032e-05	-9.266100e-08	0.000000e+00	0.000000e+00	0.041
BLUE	G190H	0.3	1573.39	1.466481	4.570197e-05	-8.517784e-08	0.000000e+00	0.000000e+00	0.014
BLUE	G570H	0.3	4574.97	4.471405	9.366883e-05	-2.457887e-07	0.000000e+00	0.000000e+00	0.049

Table 3 - Wavelength Coverage of FOS Dispersers and Best Linear Fits

Detector	Disperser	Low λ (Å)	High λ (Å)	a	b	rms (pix)
BLUE	G130H	1150[a]	1606	1087.99	1.0055	0.229
BLUE	G190H	1573	2330	1574.10	1.4690	0.250
BLUE	G270H	2222	3301	2222.18	2.0966	0.331
BLUE	G400H	3240	4823	3241.24	3.0729	0.246
BLUE	G570H	4575	6872[a]	4574.96	4.4783	0.064
BLUE	G150L	1150[a]	2510	−1078.81	6.9610	0.113
BLUE	G650L	3540	9022[b]	−3943.30	25.1619	0.279
BLUE	PRISM	1850[b,c]	5500	...	...	...
RED	G190H	1565[d]	2312	2312.50	−1.4334	0.102
RED	G270H	2223	3278	3278.63	−2.0449	0.138
RED	G400H	3238	4784	4784.63	−2.9961	0.141
RED	G570H	4571	6820	6819.84	−4.3558	0.138
RED	G780H	6272	9219[e]	9222.56	−5.7180	0.151
RED	G150L	1600[d]	2430	2427.98	−6.8343	0.044
RED	G650L	3540	8729	8720.22	−24.5626	0.045
RED	PRISM	1850[c]	8950[e]	...	...	...

[a]Short wavelength end set by MgF_2 cutoff.
[b]Quantum efficiency of the blue tube is very low beyond 5500 Å.
[c]Short wavelength end set by sapphire cutoff and large dispersion of the prism.
[d]The quartz window of the red detector attenuates sharply below 1650 Å.
[e]Quantum efficiency of the red tube is very low beyond 8950 Å.

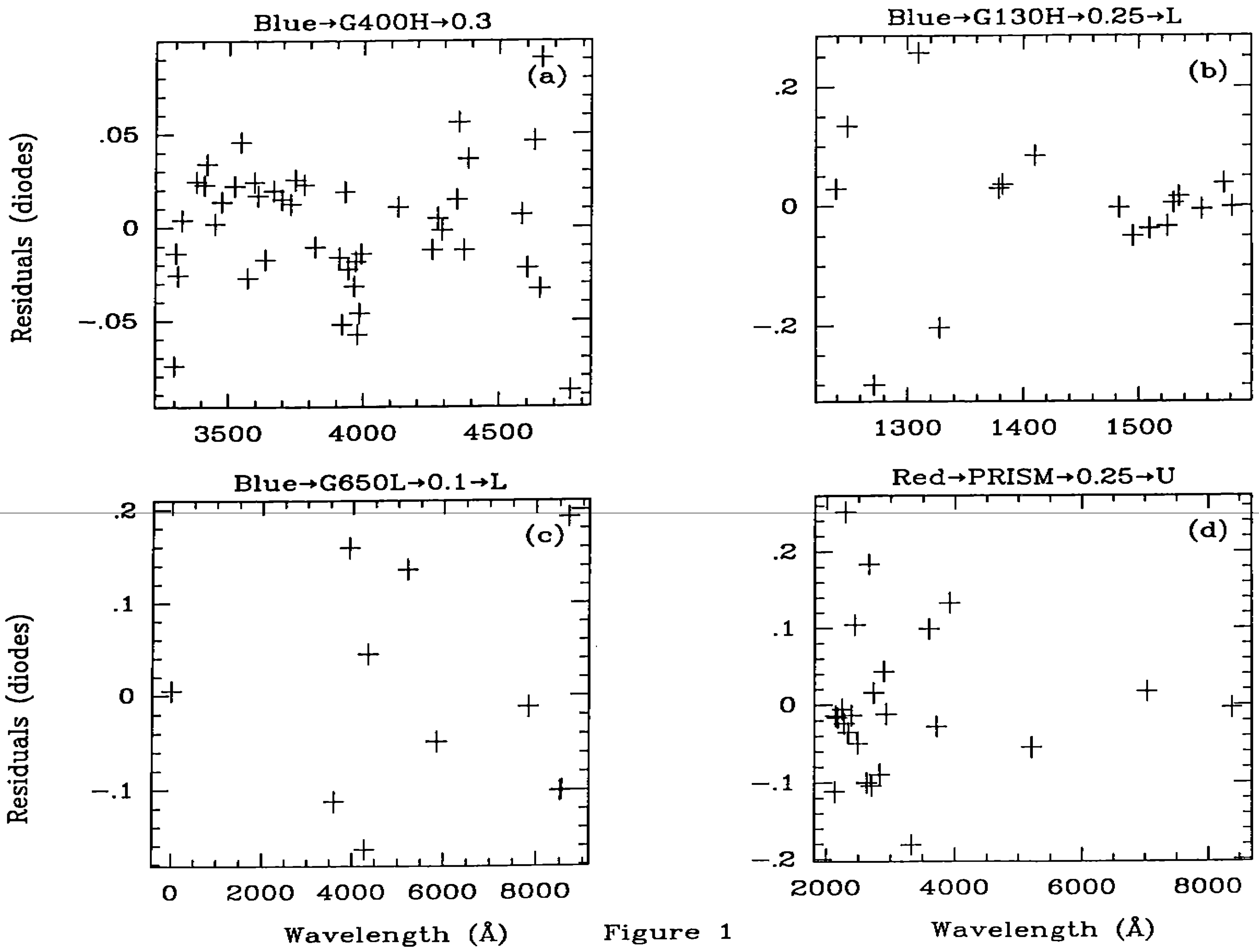
Blue→G400H→0.3
(a)
Blue→G130H→0.25→L
(b)
Blue→G650L→0.1→L
(c)
Red→PRISM→0.25→U
(d)
Residuals (diodes)
Wavelength (Å)

Figure 1