SPECTROPHOTOMETRIC STANDARDS FOR HST AND THE UV CALIBRATION OF *IUE**

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ABSTRACT: The Hubble Space Telescope (HST) will require many spectrophotometric and photometric standards for the calibration of the 6 scientific instruments, which can detect photons from 1050 - 11000 Å. The standard stars and standard fields for this wavelength range are specified in 3 of the documents of the 6 part series entitled "STANDARD ASTRONOMICAL SOURCES FOR HST." In particular, the UV flux standards in the 1150 - 3200 Å range are established by a joint NASA/ESA program of observation and recalibration of the low dispersion spectrophotometry from the International Ultraviolet Explorer (*IUE*). The recalibration includes corrections for the change in *IUE* sensitivity with time, as well as a new absolute flux calibration based on a comprehensive set of recent observations of the OAO-2 standard stars. The *IUE* sensitivity loss was as much as 20% in the 2200 - 2300 Å range, while the absolute flux scale changes by more than 10% in the 1400 Å region. The goal of the UV calibration program is a 10% external accuracy and a 2% internal consistency over a brightness range of more than 5 orders of magnitude.

1. INTRODUCTION

The Hubble Space Telescope (HST) will require many types of standard sources for a diverse range of calibrations to be performed after launch. The scientific instruments are sensitive to a wide range of wavelengths from 1050 to 11,000 Å and encompass a broad range of measurement capabilities including astrometry, photometry, imaging, polarimetry, and spectroscopy. To verify proper operations of each instrument and to provide quantitative calibrations, a diverse range of standard sources and fields are required.

The background material for the choice of calibration targets comes from the individual instrument teams, which have the responsibility for calibrating their scientific instrument during the first six months after launch. At the end of the six-month period, calibration becomes the responsibility of the ST ScI. Therefore, cooperation

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and joint planning of calibration efforts is imperative for all concerned parties. Through an intercomparison of all of the team plans, the centralization of the calibration planning at the ST ScI leads to the identification of omissions and the establishment of a common basis for calibrations among the different instruments.

Table 1 contains the list of calibration target categories and the scientists who are contributing. The first name listed is the scientist at the ST ScI who is leading the effort to obtain a consensus on the requirements for each instrument and to identify a minimal set of targets that satisfy the complete matrix of requirements.

For three of the target categories in Table 1, UV, optical and polarimetric, there are requirements for accurate spectrophotometry. J. B. Oke has a presentation on some of the work being done on the HST optical spectrophotometric standards, while K. Horne will explain how to use the standard star spectrophotometry to calibrate the HST instruments on a common photometric basis. I am the leader of the effort to obtain a set of UV standards using the *IUE* spacecraft.

2. REQUIREMENTS FOR UV STANDARDS

Five of the six HST scientific instruments are sensitive in the ultraviolet and will observe UV spectrophotometric standard stars for absolute photometric calibration and other reasons. An important goal is to identify a minimum set of stars that will meet all HST calibration requirements. The aim is to make the most efficient use of HST observing time while minimizing the effort required to collect standard star data in advance of launch. In the magnitude range of 12 to 16 that is accessible to all five instruments, a special effort was made to include high ecliptic latitude stars that would be available to HST at any time. New optical spectrophotometry of the proposed standards is being obtained (see contribution here by Oke). We have avoided reliance on any individual star and have also avoided using strong-lined stars, where practical. The proposed standards cover a large magnitude range to allow linearity checks.

Because of the requirements of HRS and HSP for brighter targets, the complete *IUE* program is to obtain spectrophotometry of hot stars in low dispersion from the bright limit of second mag to the faint limit of ~ 16 mag with a spacing of about one mag. Figure 1 shows the current set of *IUE* spectra for 30 of the hot standard stars. Multiple spectra have been co-added in all cases, but the fainter stars still have relatively poor signal-to-noise ratios, especially in the 2000 - 2500 Å region where the long wavelength *IUE* cameras have poor sensitivity. A more complete rationale for the UV standard star program is in Bohlin *et al.* (1987) along with a complete target list and finding charts.

TABLE 1

STANDARD ASTRONOMICAL SOURCES FOR HST

CATEGORY	AFFECTED INSTRUMENT	STUDY TEAM MEMBERS
1. UV Spectrophotometric	FOC, FOS, HRS, HSP, WFPC	R. Bohlin, J. Blades, A. Holm, B. Savage, D.Turnshek
2. Optical Spectrophotometric and Photometric	FGS, FOC, FOS, HSP, WFPC	D. Turnshek, W. Baum, R. Bohlin, J. Dolan, J. Koornneef, K. Horne, J. Oke, R. Williamson
3. Wavelength	FOC, FOS, HRS, WFPC	H. Ford, L. Hobbs, D. York, D. Duncan
4. Astrometric	ALL 6	A. Fresneau, R. Bohlin, P. Hemenway, B. Marsden, K. Seidelman, W. van Altena
5. Polarimetric	FOC, FOS, HSP, WFPC	O. Lupie, H. Stockman, R. Allen, A. Code, J. Dolan, D. Turnshek, R. White
6. Spatially Flat Fields	FOC, FOS, HRS, HSP, WFPC	C. Cox, R. Bohlin, R. Griffiths, T. Kelsall

Notes to Table 1.

FGS - Fine Guidance Sensor. This instrument was built by the Perkin Elmer Corporation for the primary purpose of fine pointing the Space Telescope. The FGS can also be used for astrometry, and these scientific uses are directed by an astrometry team led by W. Jeffreys at the University of Texas.

FOC - The Faint Object Camera has been developed by the European Space Agency. P. Jakobsen is the Project Scientist, replacing F. Macchetto, who is now the science team leader.

FOS - Faint Object Spectrograph. The principal investigator is R. Harms from the University of California at San Diego and the Applied Research Corporation.

HRS - High Resolution Spectrograph. The principal investigator is J. Brandt of the University of Colorado.

HSP - High Speed Photometer. The principal investigator is R. Bless of the University of Wisconsin.

WFPC - Wide Field and Planetary Camera. The principal investigator is J. Westphal of the California Institute of Technology.

3. INTERNAL CONSISTENCY OF *IUE* SPECTROPHOTOMETRY

IUE routinely obtains spectra of point sources in a small 3 arcsec aperture (S), a large 10 by 20 arcsec oval aperture (L), or by trailing the point source along the length of the large aperture (T). The early *IUE* calibration work used an average of spectra from both the large and the small entrance apertures with the assumption that their relative response was gray over the entire spectral range. Since recent studies have shown that the small-aperture sensitivity drops by as much as 30% at 3200 Å in the LWR camera, an error as large as 10% at 3200 Å was present in the *IUE* calibration when applied to a large-aperture spectrum.

Figure 2 is a plot of the mean S/L response for LWR. The corresponding T/L plot in Figure 3 is flat but is systematically above unity by about 4% due to the fact that Panek (1982) underestimated the true length of the large LWR aperture by about 4%. Bohlin (1986) determined the proper corrections to the S and T spectra to bring all low dispersion spectra from SWP and LWR onto the same scale as L spectra. The absolute calibration is specified for the L mode in Bohlin (1986) and is corrected for the initial error. However, one new error that crept into Bohlin (1986) paper is an incorrect set of T/L ratios for LWR. The proper LWR T/L ratios appear in Table 2. The S/L and T/L ratios for the LWP camera remain to be determined.

The other big problem in the internal photometric consistency of *IUE* data is the change in sensitivity with time. Bohlin and Grillmair (1988a,b) have determined a precise correction technique for 5 Å bins for SWP and LWR low dispersion spectrophotometry. Figure 4 demonstrates that the precision is better than 1% for the SWP, while Figures 5 - 6 show the similar results for LWR. Figure 7 shows that the LWR correction technique of Clavel, Gilmozzi, and Prieto (1988) is less precise.

The spectra used to construct Figures 4 - 6 are averages of L, S, and T spectra with the appropriate S/L and T/L correction. The combination of these aperture corrections and the corrections for the change in sensitivity with time demonstrate that a large ensemble of *IUE* data can be corrected to better than 1%. A more relevant test of the accuracy for the HST standard star spectra is shown in Figures 8 - 9, where spectra taken with the same technique and observed in the same time frame as the bulk of the HST standard star data are compared to the same 1978-9 baseline as in Figures 4 - 6. Even for the HST data, where heavier exposures are used to bring up the signal for regions of low sensitivity, the set of 4 stars is again within 1% of the baseline (Figure 8). However, one of the 4 stars, BD+75°325, has a flux that is systematically high by 1.8% (Figure 9). Thus, the limiting internal consistency of the set of HST standard star spectra may be as good as 2%.

TABLE 2

CORRECTED[a] TRAIL SENSITIVITY FOR LWR

λ (Å)	T/L[b]	λ (Å)	T/L[b]	λ (Å)	T/L[b]
1850	1.058	2350	1.038	2850	1.043
1900	1.056	2400	1.039	2900	1.043
1950	1.053	2450	1.040	2950	1.044
2000	1.051	2500	1.040	3000	1.046
2050	1.049	2550	1.040	3050	1.053
2100	1.047	2600	1.041	3100	1.063
2150	1.045	2650	1.041	3150	1.068
2200	1.043	2700	1.041	3200	1.070
2250	1.041	2750	1.042	3250	1.070
2300	1.039	2800	1.042	3300	1.070
				3350	1.070

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[a] The values of T/L for LWR in Bohlin (1986) are wrong and should be replaced by this Table.

[b] Ratio of trailed response to point sources in the large aperture. The absolute calibrations are related by

$$S^{-1}(\text{Trail}) = S^{-1}(\text{LAp})/(T/L).$$

The values of T/L are for trailed exposure times computed using lengths for the large apertures of 21″.4 for SWP and 20″.5 for LWR (Panek 1982)

The LWP camera shows much less loss in sensitivity than LWR; and a correction for the change in sensitivity over the relevant years of 1983 - 1988 may not be necessary to achieve the 2% internal accuracy goal (cf. Sonneborn and Garhart 1987).

Another check on the photometric consistency is to compare ANS photometry to the mean *IUE* fluxes averaged over the ANS bandpasses as shown in Figure 10. The one sigma scatter of the points about the mean are 2.4% (1550 Å), 2.5% (1800 Å), 4.0% (2200 Å), and 4.6% (2500 Å). The increase in scatter in the longer wavelength bands is probably due to a systematic difference between the LWP and LWR flux scales; all 5 LWR fluxes fall below the rest of the points in the 2200 Å band. Once again, the expectation of a 2% internal consistency is not unreasonable, even over the entire dynamic range of Figure 1.

4. ACCURACY OF THE ABSOLUTE *IUE* FLUXES

Once the photometric repeatability of the low dispersion *IUE* spectrophotometry is established, the accuracy of the *IUE* fluxes depends on the precision of the fluxes of the reference standard stars used to calibrate *IUE* and on the fidelity of the transfer of the calibration.

The flux for η UMa and for the other OAO-2 and TD-1 reference standards is specified by Bohlin *et al.* (1980) and by Bohlin and Holm (1984) to an estimated accuracy of 10%. Figure 11 shows all the independently determined UV flux measurements for η UMa. This plot was used to draw in a guess for the true η UMa flux, which defined correction factors for the published flux catalogs, including the OAO-2 and TD-2 reference standards used to calibrate *IUE*. Bohlin (1986) demonstrated that *IUE* fluxes are in reasonably good agreement with ground based fluxes at the longest wavelengths and with Voyager spectrophotometry at the shortest wavelengths.

Originally in 1979 - 1980, the transfer of the reference star flux scale to *IUE* was done to an inadequate precision, because the *IUE* spectra of the bright OAO-2 standards were too few and of poor quality. In the 1984-5 time frame, the *IUE* project obtained a vastly superior set of spectra of the 6 OAO-2 standard stars for the purpose of a comprehensive recalibration. The change in the *IUE* absolute flux calibration that is indicated by the upgraded set of spectra is shown in Figures 12 - 13 for SWP and LWR. Some similar work remains to be done on the LWP absolute calibration.

Beyond the steps outlined above, further improvements in the *IUE* absolute flux scale could come from rocket experiments to make precise stellar flux measurements or from comparison with theoretical flux distributions of white dwarf stars. New rocket flights do not seem to be in the cards; but the preliminary results from comparisons of white dwarf models with *IUE* data by J. Holberg and D. Finley are shown in Figures 12 - 13. Unfortunately, the recalibration and models do not agree, but there is some similarity in the shapes of the curves. Perhaps, the mean level of the theoretically based calibrations would be closer to the level of the recalibration, if slightly cooler model flux distributions are used.

I thank the staff at the Goddard Space Flight Center, who made the data available and are always ready to cheerfully discuss any technical detail of *IUE* data.

5. REFERENCES

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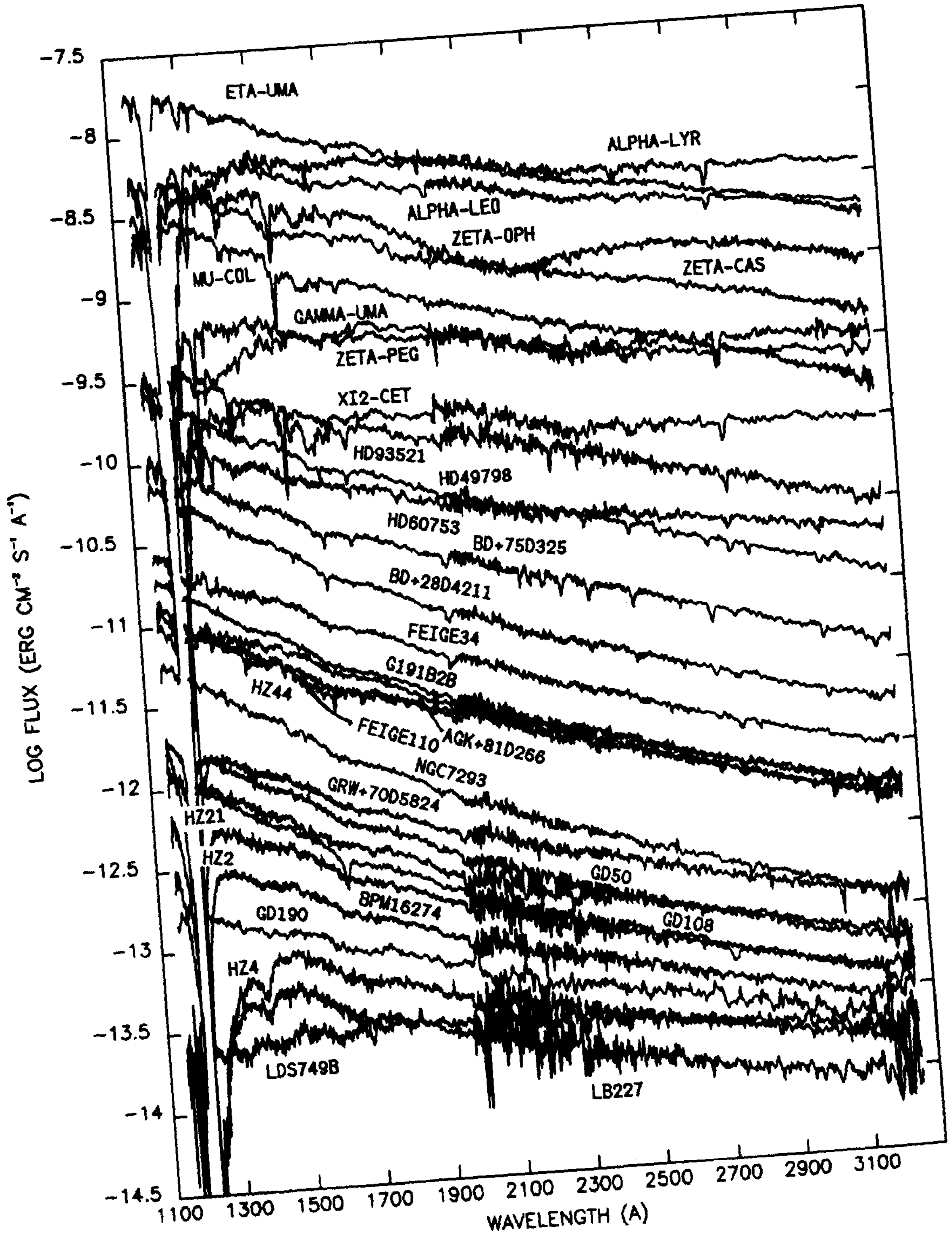

Figure 1 - Preliminary UV spectrophotometry of ST standard stars from the *IUE* spacecraft. The fainter stars were obtained at the Vilspa site using ESA time, while the brighter targets were observed at GSFC on NASA time.

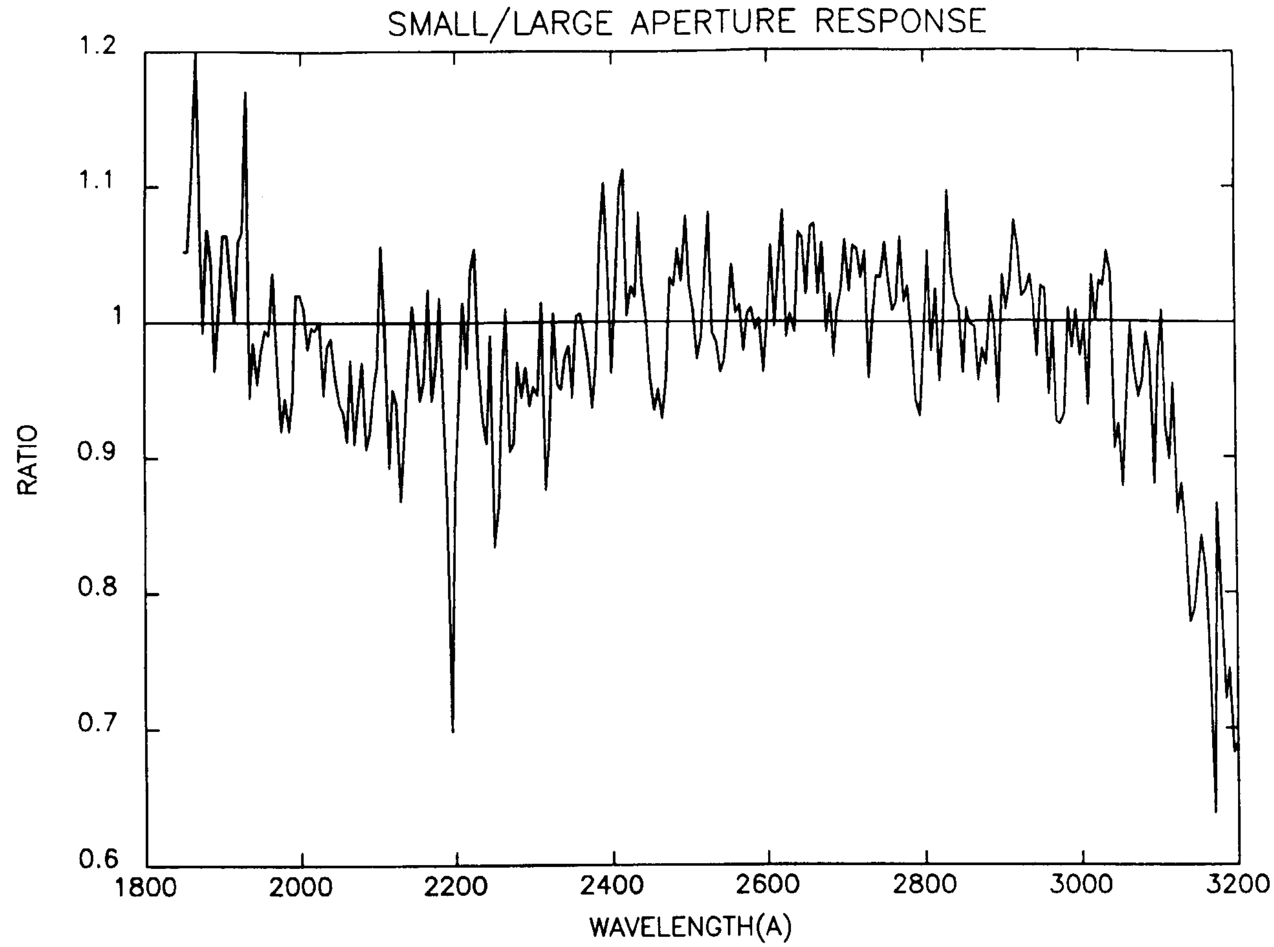

Figure 2 - Ratio of the *IUE* response to stars in the small aperture (S) to the large aperture (L) for LWR. Since the small aperture is not photometric but transmits about 50% of the starlight, the approximate normalization to unity is achieved by multiplying the actual ratio by 2. A total of 58 S and 77 L spectra of the 5 *IUE* standards are combined to define the S/L ratio.

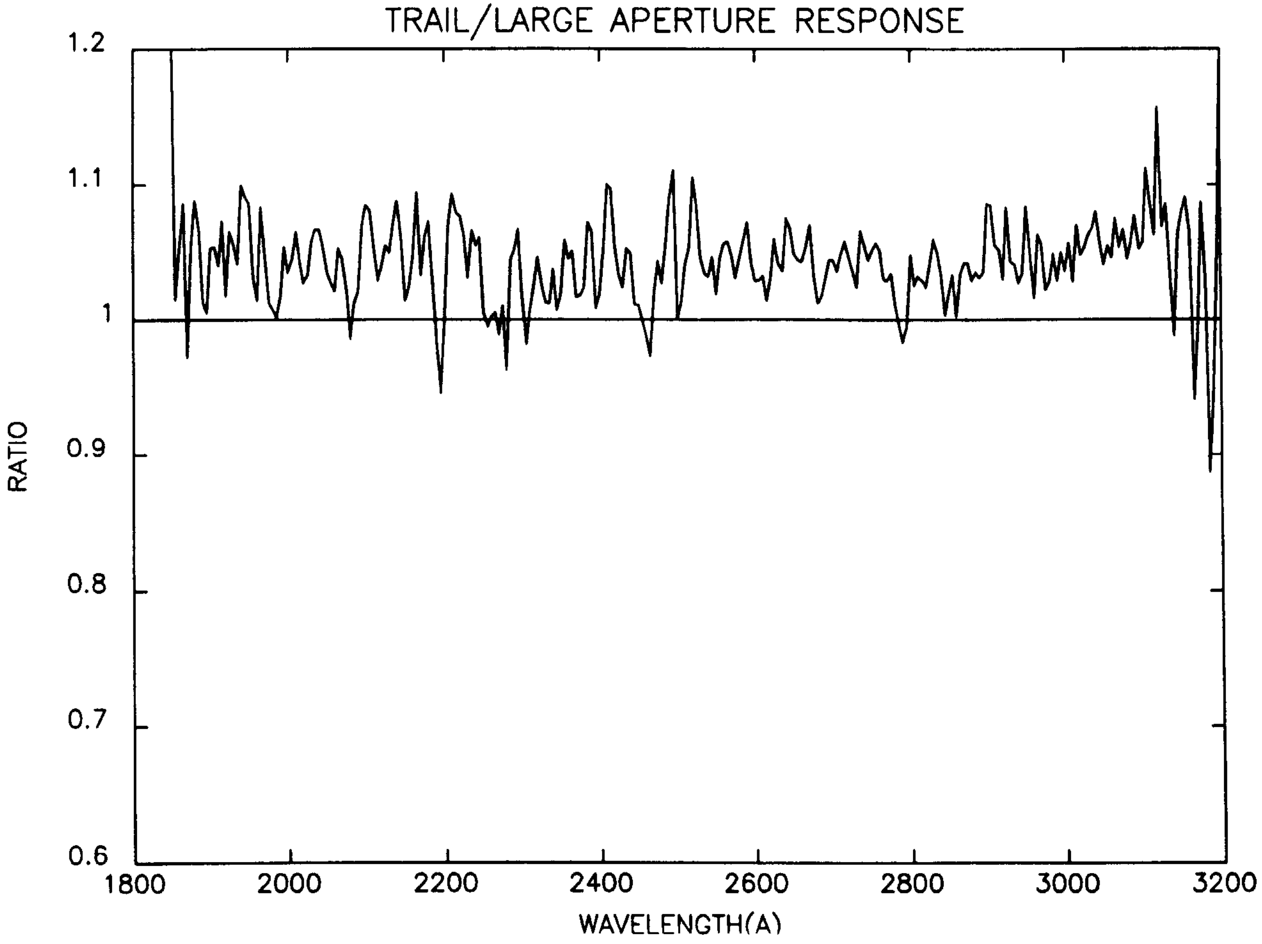

Figure 3 - Ratio of trailed (T) to L response for LWR. A total of 92 T and 272 L spectra define this T/L ratio.

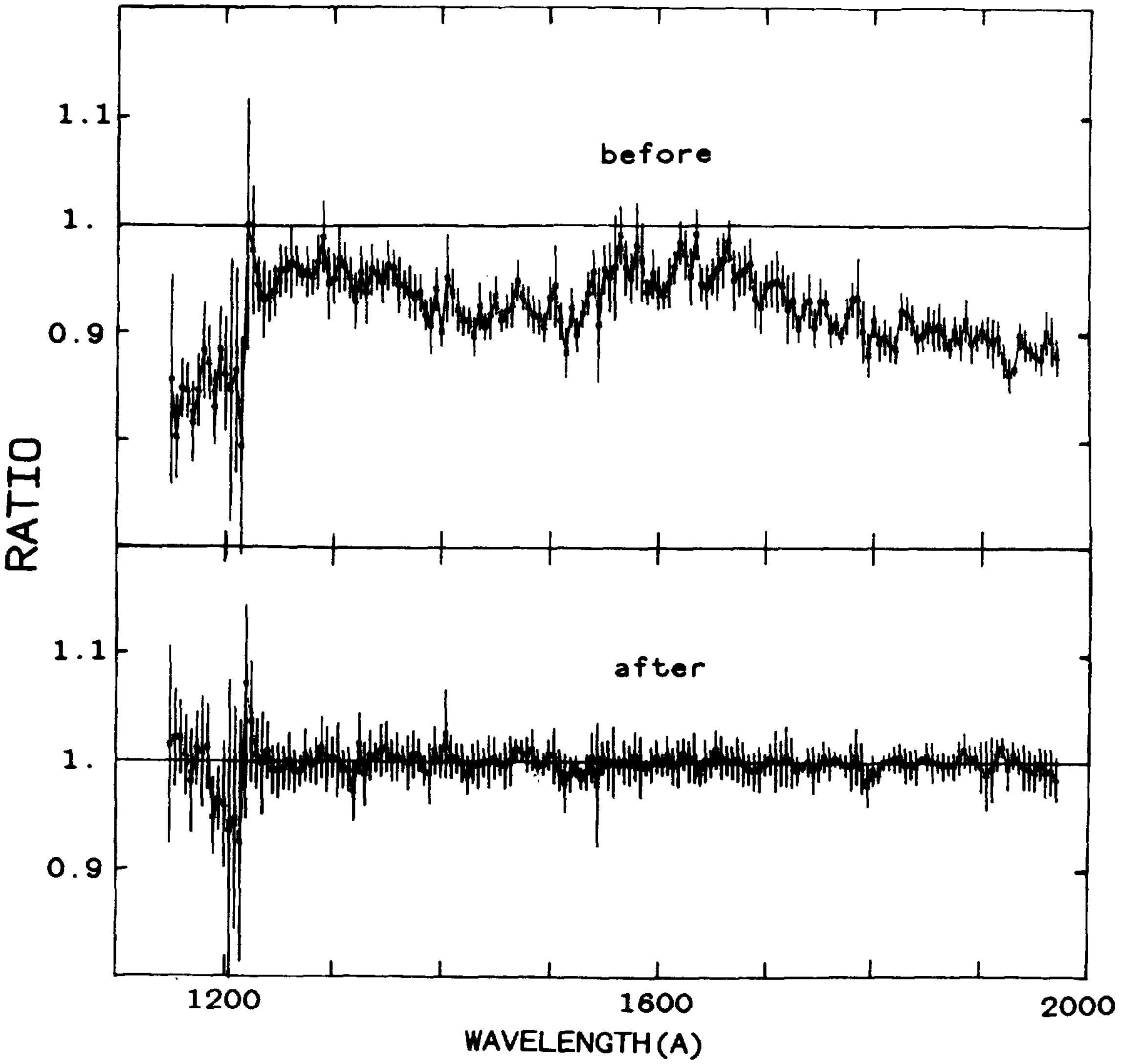

Figure 4 - Mean ratio of the five standard stars in 1985 to the baseline 1978 fluxes in 5 Å bins, before and after correction for the change in sensitivity. The error bars are the one-sigma scatter among the five individual ratios. The large glitch near the strong Lα absorption is caused by the division of fluxes that approach zero and by small wavelength errors that have a large effect on the 5 Å bins in the steep sides of Lα. The mean ratio from 1230 to 1970 Å is 0.929 before correction and 1.000 after correction. The rms scatter in the corrected average values is 0.8% and is indicative of the limiting accuracy of the technique, as applied to large samples of spectra. The number of spectra in parentheses follows each star for 1978 and 1985, respectively: HD60753 (41, 20), BD+75°325 (28, 30), HD93521 (34, 11), BD+33°2642 (15, 6), and BD+28°4211 (24, 19).

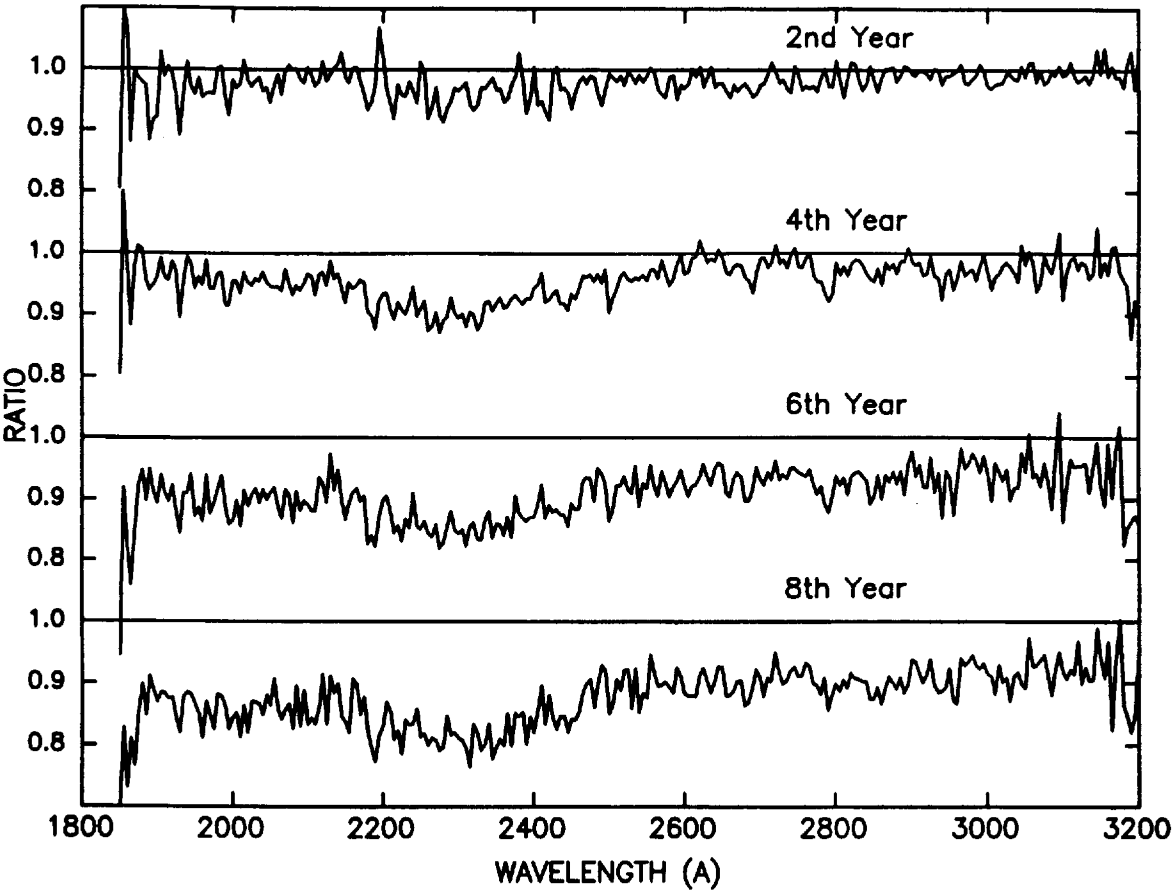

Figure 5 - Uncorrected mean ratios of the standard stars to their baseline fluxes in 5 Å bins from the 1978.36 - 1979.36 period. A total of 141 spectra are used to define the 5 baseline average spectra, while somewhat fewer spectra are available in each of the later years.

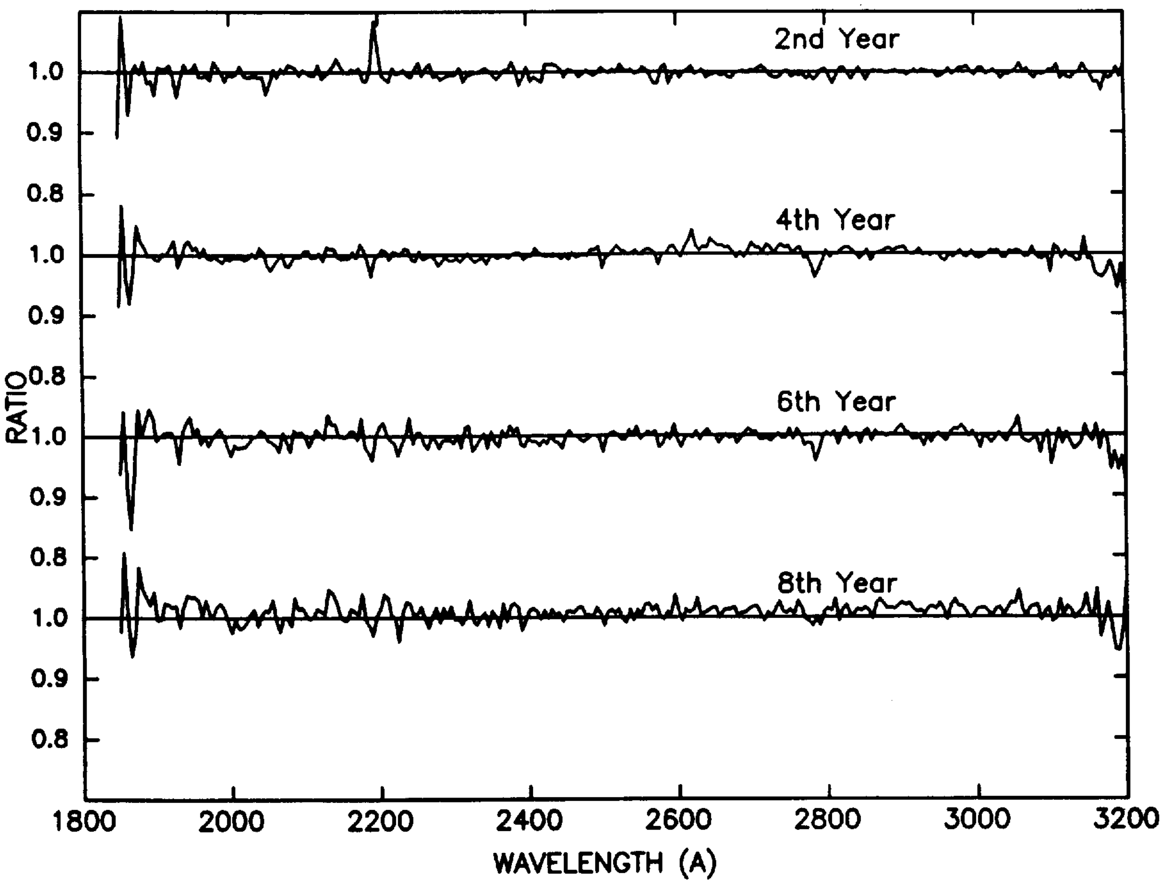

Figure 6 - Mean ratios corrected with our technique for the same data as in Fig. 5. Most of the larger glitches are caused by the bright spot near 2200 Å and the large aperture reseaux at 1855, 2055, 2580, and 2785 Å.

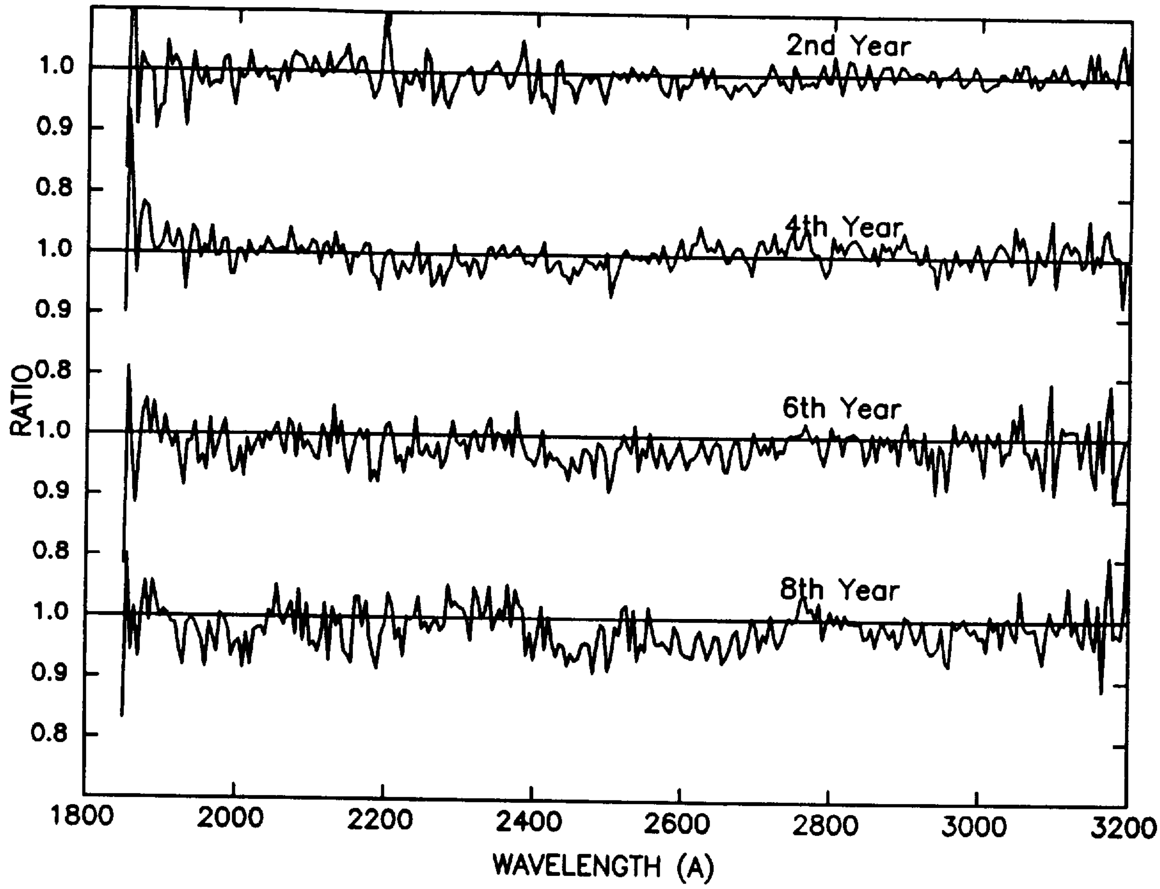

Figure 7 - Mean ratios corrected with the Clavel, Gilmozzi, and Prieto algorithm for the same data as in Figure 5 and 6.

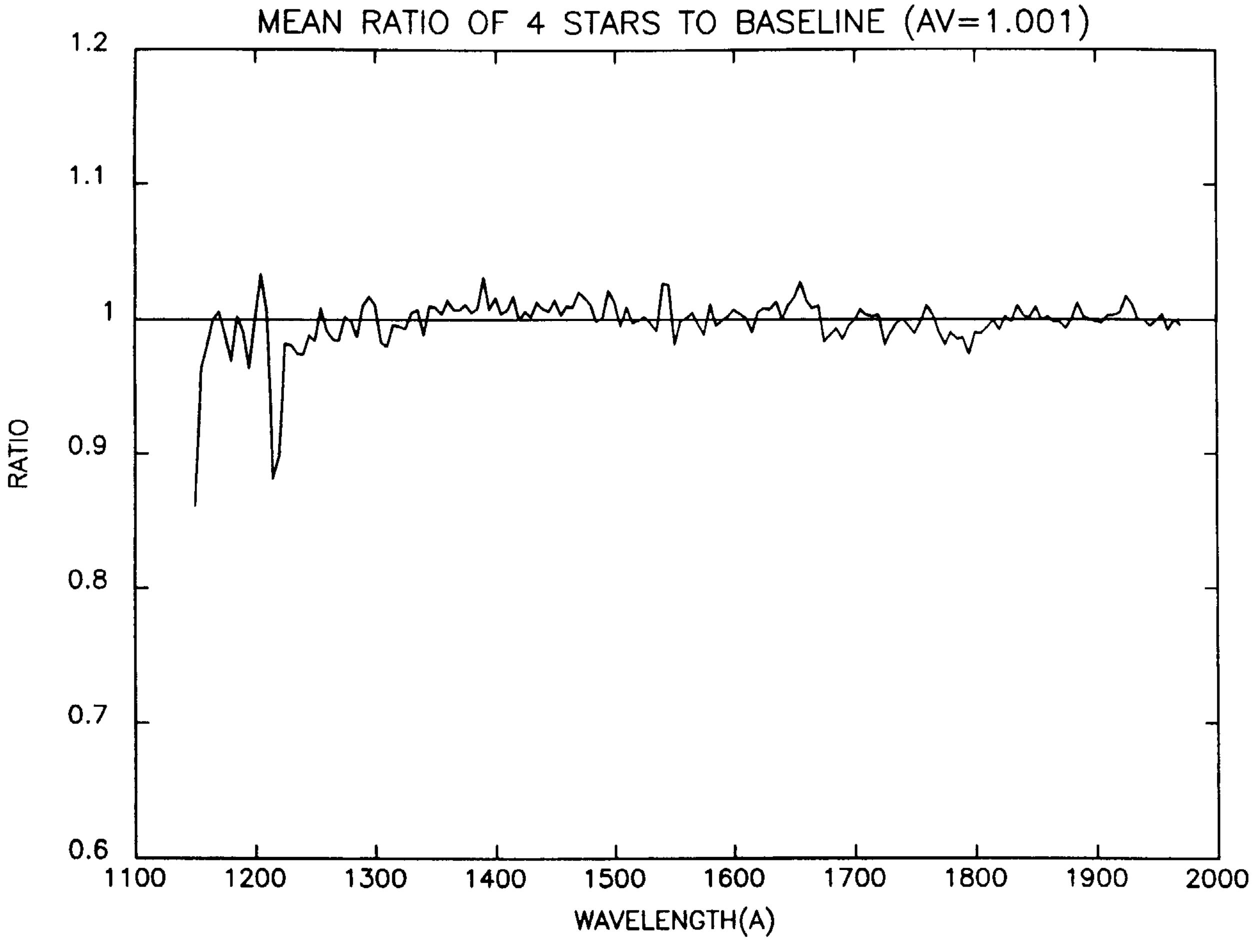

Figure 8 - Corrected mean ratios for 4 stars, HD60753, BD+75°325, HD93521, and BD+28°4211, to their baseline fluxes in the case where the numerator fluxes are observed with the same technique and in the same time frame as the bulk of the HST standard star observations.

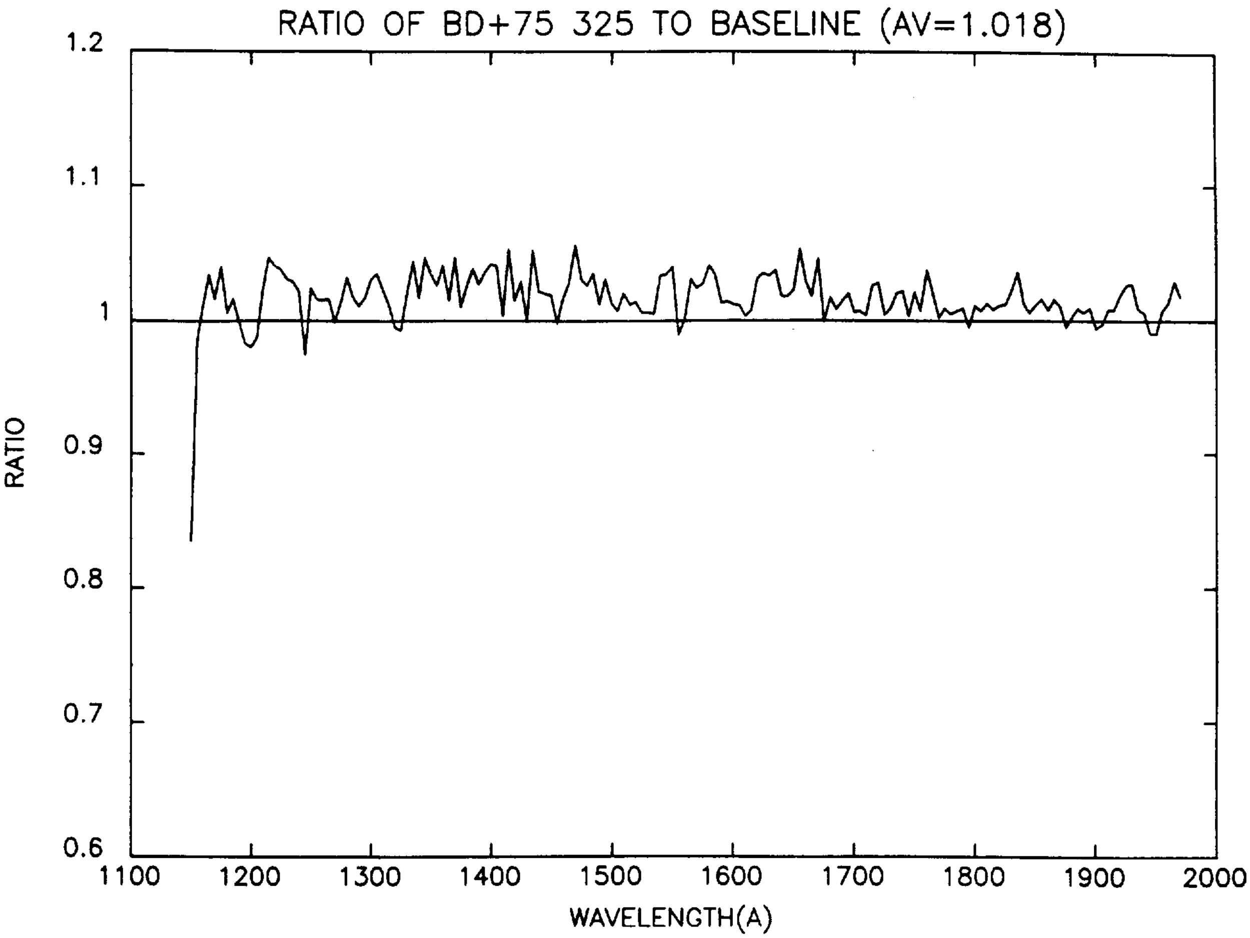

Figure 9 - Ratio of BD+75°325 to its baseline flux for the same case as Figure 8. The 1.8% systematic error may be indicative of the errors in the internal consistency of the HST UV standard star fluxes.

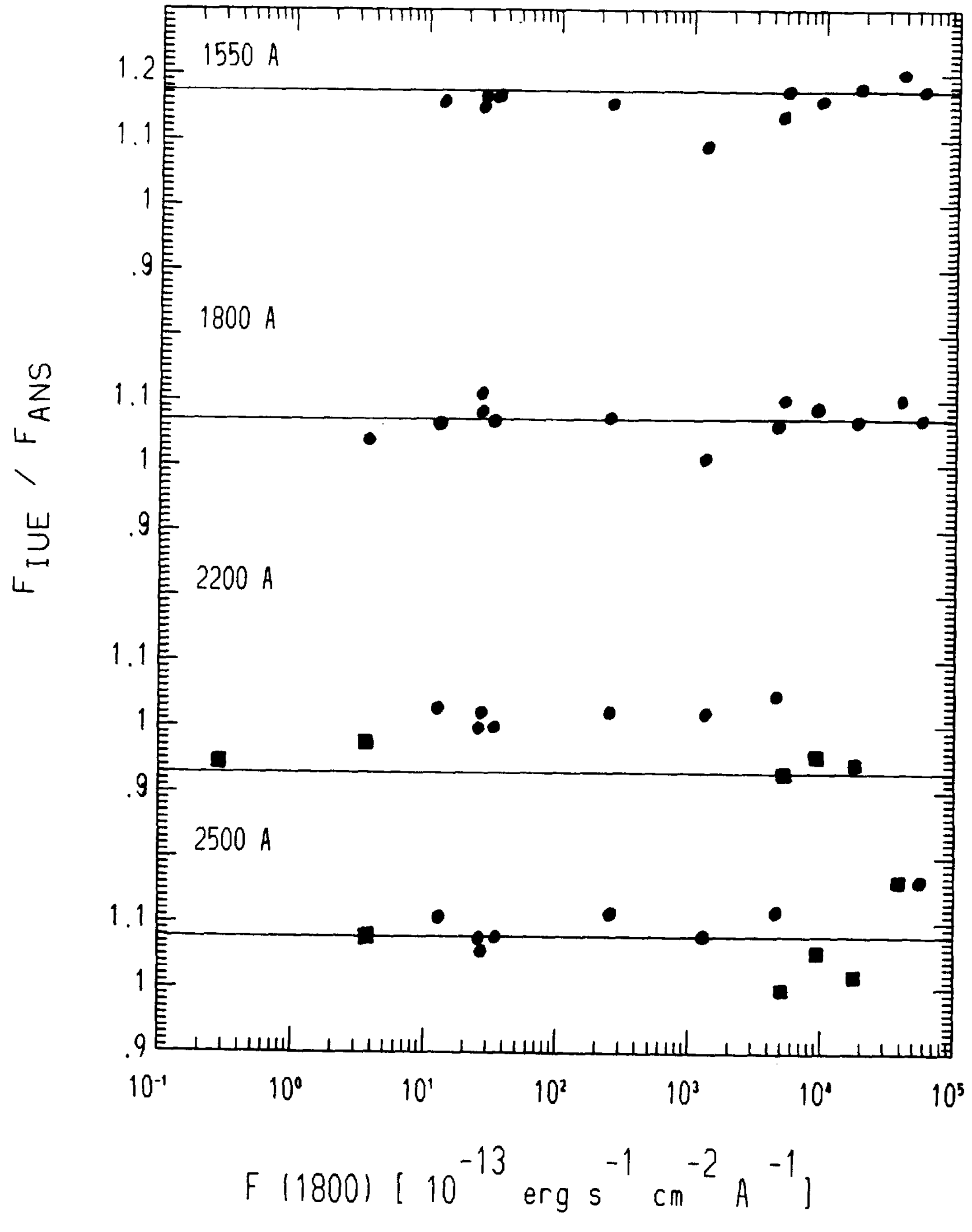

Figure 10 - Ratio of the mean *IUE* to ANS flux in the 4 ANS bands as a function of flux that ranges over 5 decades in brightness. The horizontal lines for each bandpass are at the value of the systematic difference in the absolute flux scales of the two satellites. The squares in the two long wavelength bands are based on LWR spectra only, while LWP fluxes dominate the other long wavelength data points.

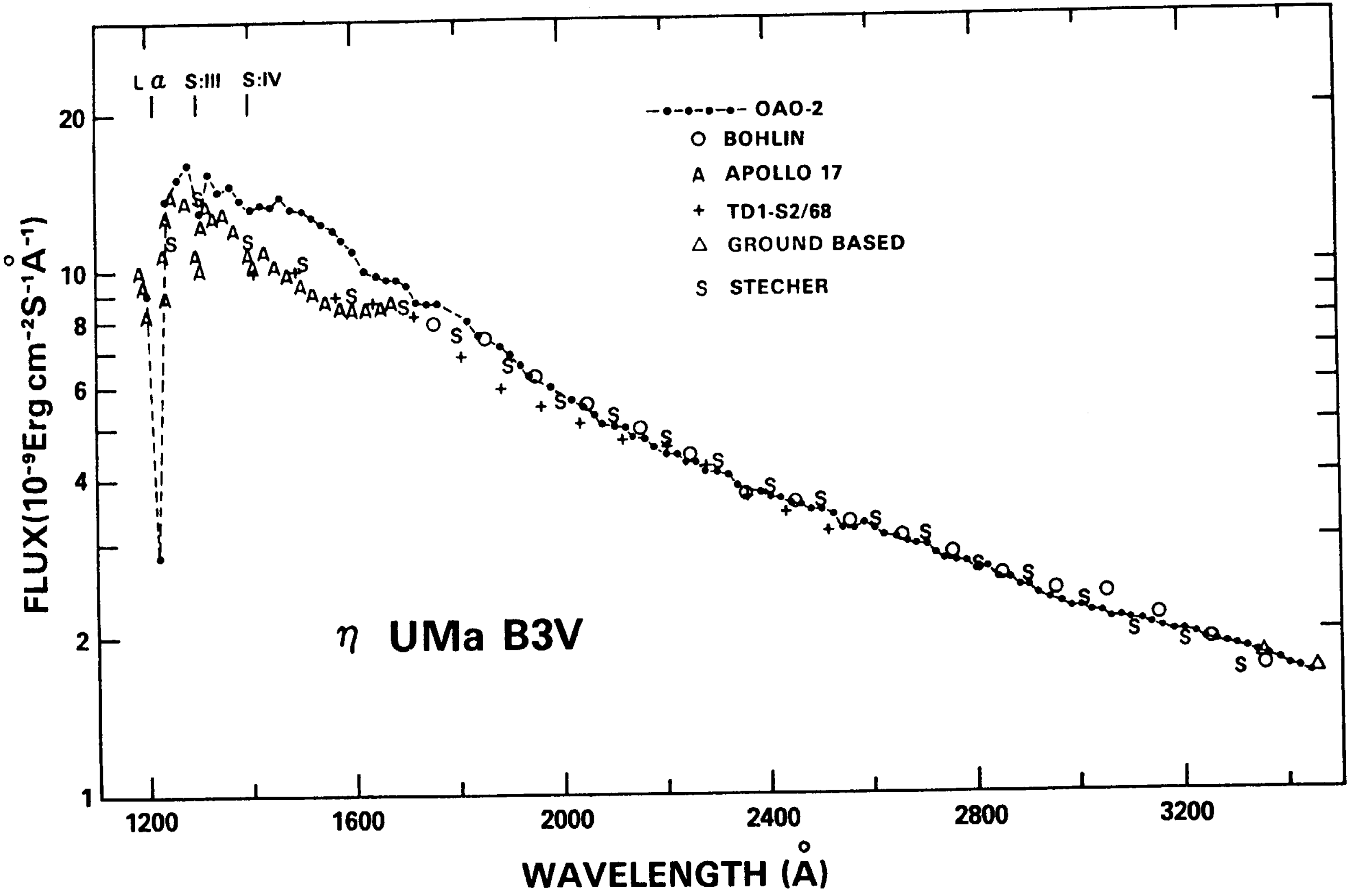

Figure 11 - Absolute flux measurements of η UMa by independently calibrated experiments.

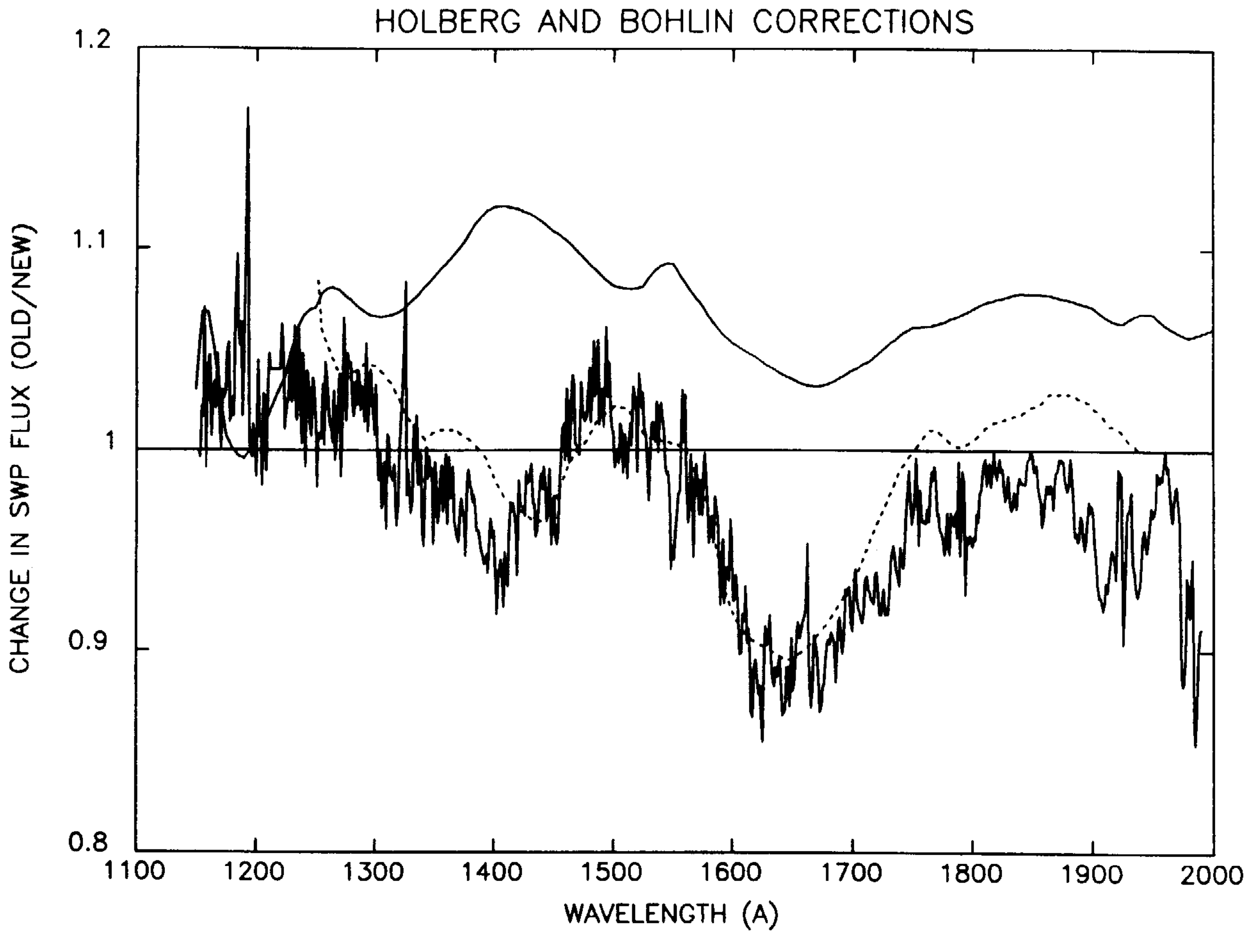

Figure 12 - Change in *IUE* SWP fluxes resulting from a comprehensive recalibration (upper smooth line) in comparison with the change required to fit theoretical models of the white dwarf G191B2B (jagged line) or BL Lac objects (dashed line). The work on white dwarfs is from J. Holberg (private communication), while Hackney, Hackney, and Kondo (1982) have produced the dashed line.

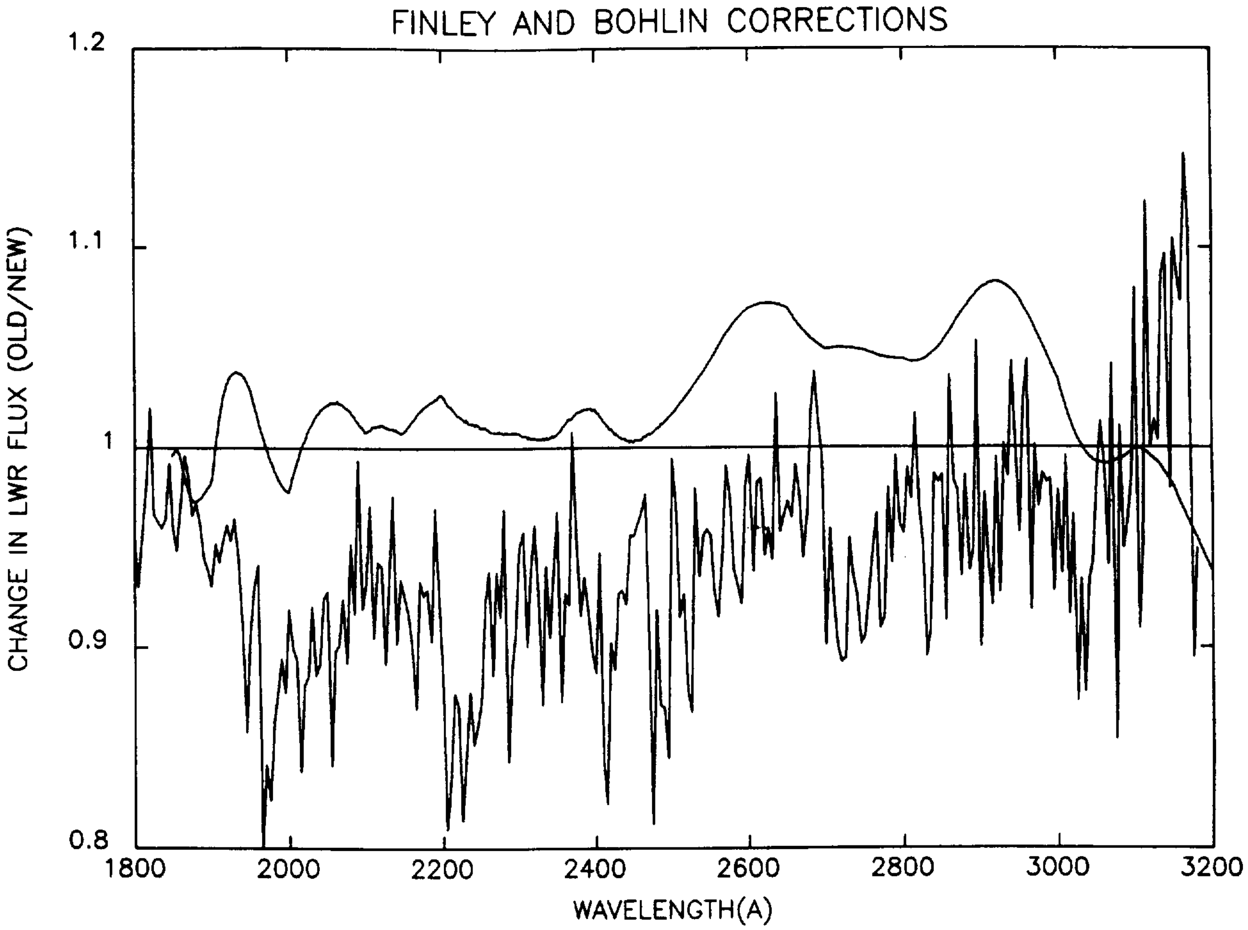

Figure 13 - As in Figure 12 for LWR. D. Finley (private communication) provided the mean result for the comparison with white dwarf models (jagged line).