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Average Inverse Sensitivity Recalibration of Pre-COSTAR Faint Object Spectrograph Data and Comparison with International Ultraviolet Explorer Data

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Abstract.

We have recalibrated all pre-COSTAR archival Faint Object Spectrograph (FOS) UV and optical spectrophotometry of active galaxies and quasars in order to extract uniformly calibrated spectrophotometric data for further detailed scientific investigations. In this paper we present results of the average inverse sensitivity (*AIS*) recalibration of this large dataset. The fluxes derived from the recalibrated data are significantly different from the original pipeline calibrations, as expected, because of the revision of the photometric reference scale. We use this dataset to present statistics of the photometric accuracy in the grating overlap wavelength regions for observations spanning multiple gratings.

Where possible we have combined multiple observations to produce a single spectrum for each object with the highest possible signal-to-noise (S/N) ratio and covering the widest wavelength range. The recalibrated spectra will be published shortly as atlases and will be available also in electronic form.

As the *International Ultraviolet Explorer (IUE)* satellite data archive is an important source of historical UV spectroscopic information, combining FOS and *IUE* spectra obtained at different epochs is often necessary. Consequently, understanding how the measurable quantities depend on the individual instrumental calibrations, and how any conclusions derived from modeling the observations may vary depending on the source of the UV data, is critical. Here we present a comparison of typical FOS and *IUE* spectra.

1. Introduction

The *Hubble Space Telescope (HST)* Faint Object Spectrograph (FOS) data archive is a rich source of excellent high quality UV and optical spectrophotometric data that can be used for various scientific problems associated with individual objects or classes of objects. To effectively use these spectra to obtain meaningful scientific results, it is essential that the data be compared consistently and be calibrated as uniformly as possible. Several of our scientific investigations require a large database of uniformly calibrated spectra of active galactic nuclei (AGNs) that can be intercompared. Therefore we have recalibrated all pre-COSTAR archival FOS UV and optical spectrophotometry of AGNs, and are in the process of doing the same for the post-COSTAR data. In this paper we present the results of the recalibration of the large number of datasets from the pre-COSTAR era.

Although the FOS UV archive is important for the study of AGNs, the vast majority of UV reference data were obtained using the *International Ultraviolet Explorer (IUE)*

satellite. These data remain important since they provide historical information about the intensities of the UV continua and emission lines that is needed to constrain models of the active nucleus. Here we present a comparison of FOS and *IUE* data, so that the two UV archives can be used effectively for comparative studies.

2. Why recalibrate pre-COSTAR FOS data?

As mentioned in the introduction, consistently and uniformly well calibrated spectrophotometric data are fundamental for any observationally analyzed problem. At present, datasets retrieved from the *HST* archive are not necessarily consistently and uniformly calibrated. This problem is especially acute for pre-COSTAR data and all spectropolarimetric data. The FOS archival data are not uniformly calibrated for the following reasons.

1. The FOS pipeline calibrations used early in the *HST* mission did not consider many instrumental effects that were later identified and quantified.
2. Although the FOS pipeline used the best calibration data available at the time, further analysis enabled these calibration data to be refined, thus rendering the prior pipeline calibrations obsolete.
3. Time varying calibrations are required to correctly model the behavior of the instrument. However, earlier versions of the *FOS* pipeline did not incorporate such capabilities.
4. The FOS pipeline photometric reference scale was changed from the mean UV reference flux system to a white dwarf model for G191B2B in 1994. This change affects the photometry dramatically.

To obtain the best calibrated spectrum per object, the datasets in the *HST* archive must be recalibrated, at least for the pre-COSTAR era. For our recalibration we have used the latest pipeline calibration called the average inverse sensitivity (*AIS*) calibration.

3. What is average inverse sensitivity (*AIS*) calibration?

The latest pipeline calibration technique uses an inverse sensitivity reference file that is generated by a spline fit to the inverse sensitivities derived from an average of many observations of a number of standard stellar spectra. This "average inverse sensitivity" reference file (hence the name of the technique) is supported by many other tables and reference files that are used to account for (amongst others) temporal, wavelength dependent, and aperture dependent variations that are seen in the instrumental response. These observed variations are readily characterized and parameterized using the *AIS* calibration framework. In comparison, the previous calibration technique required reference files that were time stamped and that were to be used only for observations obtained during a specific time interval. This method did not permit accurate calibration of a temporally smoothly varying instrumental response. The *AIS* method allows us to calibrate data to a higher level of accuracy than was possible with the older calibration technique. An added advantage to the *AIS* calibration is enhanced statistical photometric accuracy, since the inverse sensitivity reference file is generated from a large number of observations. The *AIS* calibration technique was developed over several years, with improvements applied progressively to correct for deficiencies and/or photometric discrepancies identified in the recalibrated data. Indeed, the *AIS* reference files incorporate corrections in the wavelength overlap regions of adjacent gratings derived based on inconsistencies discovered while generating the AGN atlases (Evans, Koratkar, & Pesto, 1998; and Koratkar, Evans, Blitz, & Pesto, 1998).

The *AIS* method for flux calibrating FOS data incorporates four major improvements when compared to the previous flux calibration technique.

1. Normalizing count data from all apertures to the 4.3″ aperture.

2. Correcting wavelength dependent aperture throughput to account for changes in aperture throughput as a function of the optical telescope assembly focus;

3. Correcting the data for time-dependent detector sensitivity degradation;

4. Scaling the data to the white dwarf photometric reference scale.

Below we discuss how these changes affect the final recalibrated output data.

4. The sample and the overall changes seen in the data due to recalibration

We have obtained all *HST* pre-COSTAR (UV and optical) *FOS* spectrophotometric archival data for AGNs. This sample consists of 933 datasets and 263 objects. Of these, 112 targets have observations with only one grating. These 933 datasets are AIS recalibrated using the latest pre-COSTAR reference files adopted in March 1996.

4.1. Photometry

Figure 1 shows for a typical observation the differences between an *AIS* recalibrated spectrum and the spectrum available from the *HST* data archive. For most pre-COSTAR data recalibration changes the photometry by 10–40%. The most dramatic changes occur in the UV because of the difference between the old and new photometric reference scales.

4.2. Grating overlap statistics

Where possible, the recalibrated spectra are combined carefully to produce a single high quality, complete wavelength coverage UV-optical spectrum for each object. From Figure 1 we see that the *AIS* recalibration improves the photometry at the ends of each grating, and provides improved photometry in the grating overlap regions (around 1600Å and 2300Å). Before combining any spectra the observational consistency of the datasets is investigated. Figure 2 shows a typical spectrum produced by combining multiple observations and spectra obtained using several gratings.

Such multiple grating observations were obtained for only 151 objects in the present sample from which we have generated the overlap statistics (see Table 1 and Figures 3, 4, and 5).

As can be seen from Table 1, the photometric consistency between spectra from adjacent gratings in the grating overlap regions is no greater than $\sim$5%. In general, the spline fits to the inverse sensitivity data near the ends of the grating wavelength regions are not as well constrained as the fits in the center of the grating wavelength regions. Consequently, the photometric accuracy near the edges of the grating is worse than near the center of the grating. Thus, an error of 5% in the grating overlap region photometry does not imply that the photometric accuracy at the grating center is as bad as 5%. The latter may be significantly better. We find that the grating overlap statistics for our sample are slightly worse than expected from observations of calibration standard stars, but routine (non-calibration) observations often employ less accurate target acquisition procedures, and scattered light corrections may be less well determined for many AGN with strong continua.

Figure 1. A comparison of the *AIS* calibrated spectrum with the *HST* archival spectrum for a typical AGN observation. The lower panel shows the ratio of the recalibrated spectrum to the archival spectrum.

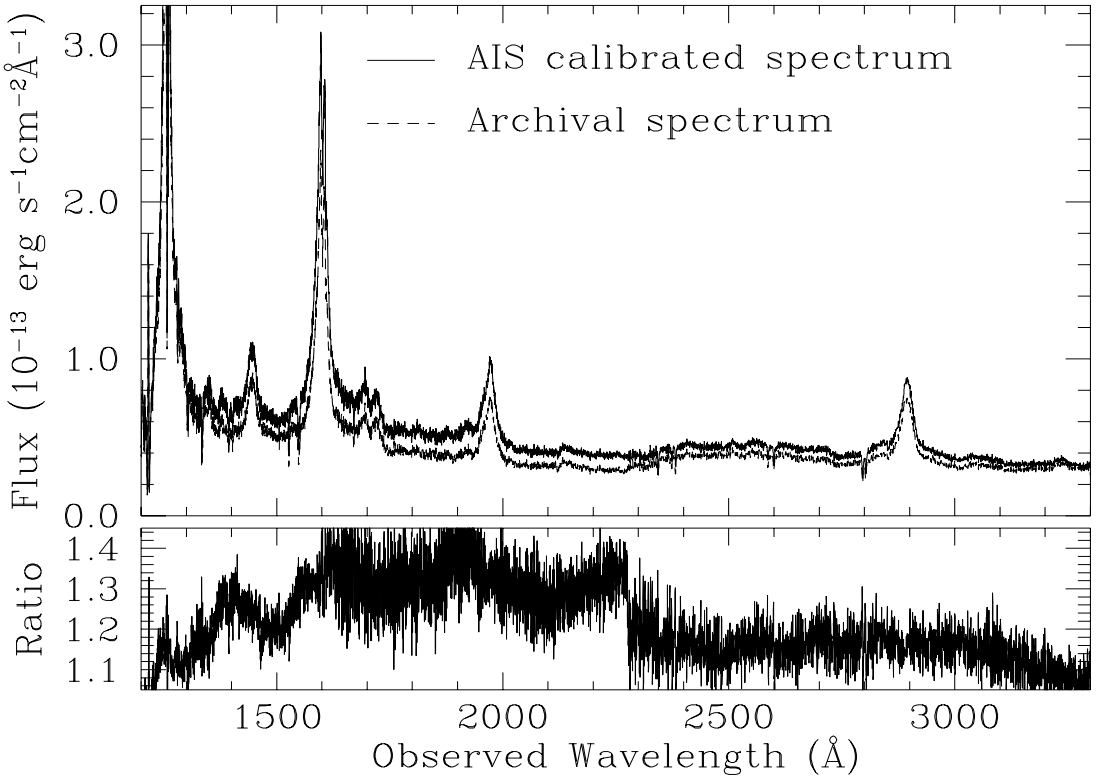


Table 1. Grating Overlap Statistics

Grating Type	Mean[a]	Median[a]
High Resolution	0.99	0.98
High Resolution Red-Blue	0.92 (1.31)	0.92 (0.88)
High Resolution Blue-Blue	0.99 (0.98)	0.99
High Resolution Red-Red	0.98 (0.99)	0.97 (0.98)
High Resolution-Low Resolution[b]	1.00 (1.35)	1.02
NGC 5548 [c]	1.00	1.00

[a]The values in parentheses are for the entire sample, while the quoted values are for the "good" overlaps which range from 0.8 to 1.25.

[b]The low resolution grating is the G160L.

[c]This is for a uniform sample of 39 overlaps between the blue detector G130H and G190H gratings. The 1σ for this distribution is 0.18, and is dominated by the two points at 1.3 in Figure 5.

Figure 2. A typical spectrum that is a coaddition of a number of gratings, from the AGN atlases.

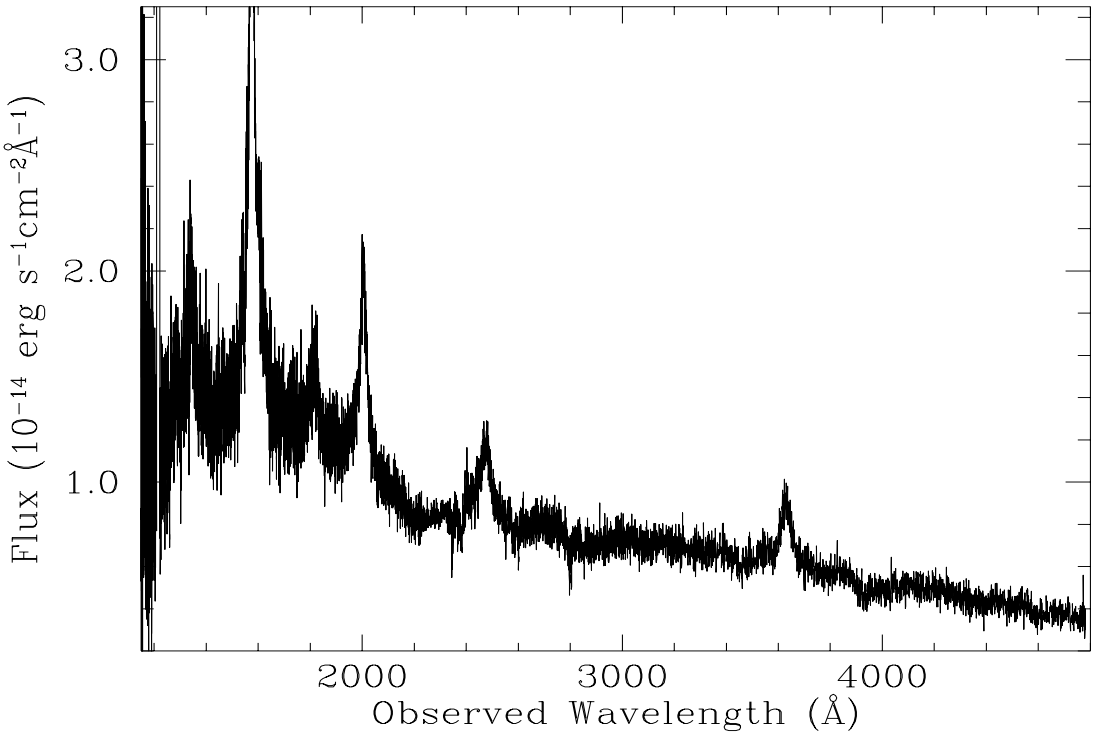


Figure 3. Grating overlap statistics for all the high resolution gratings.

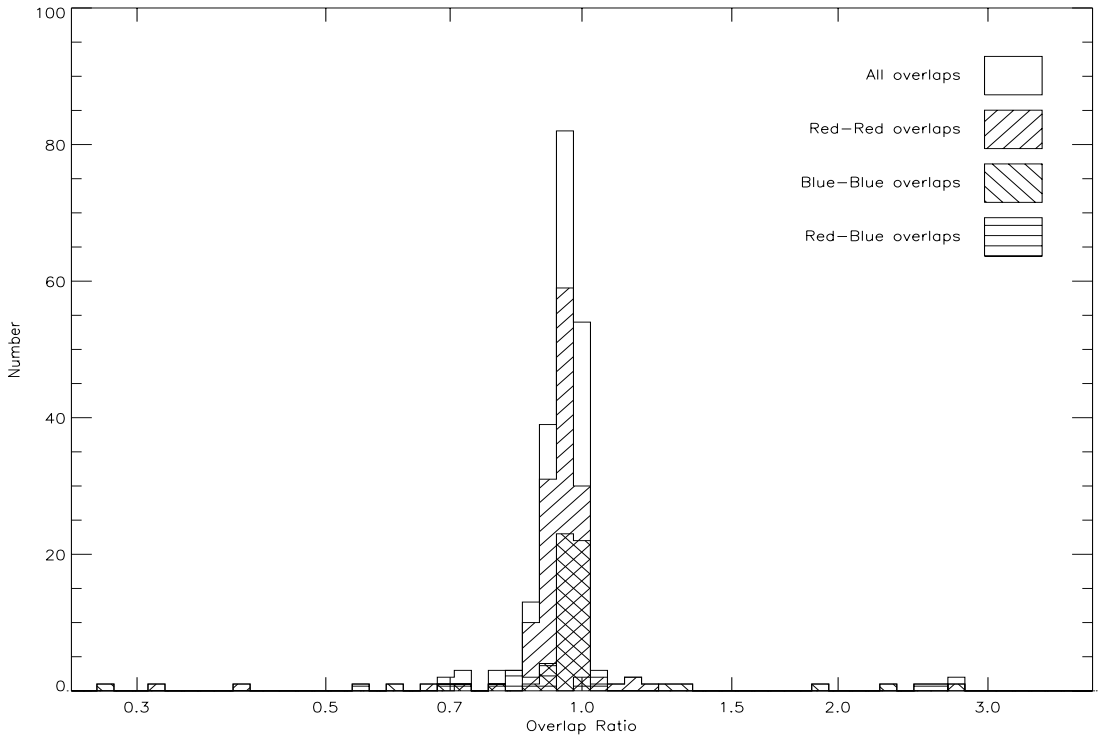


Figure 4. As Figure 3, but for the limited range of overlap ratios centered around unity.

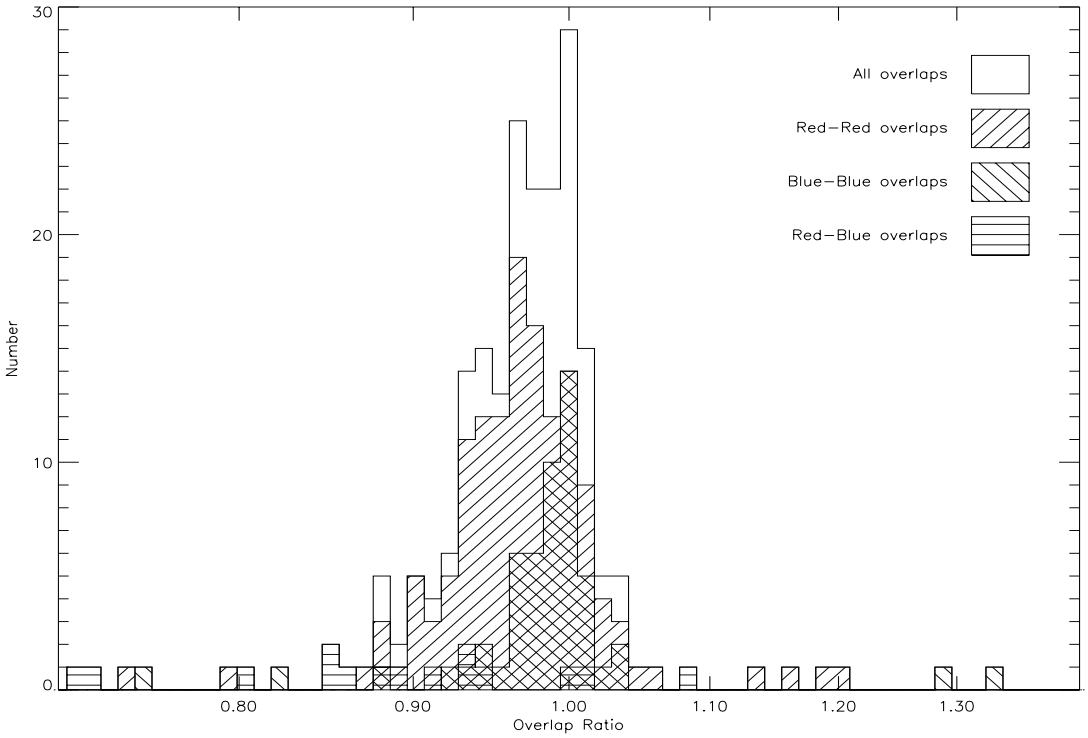
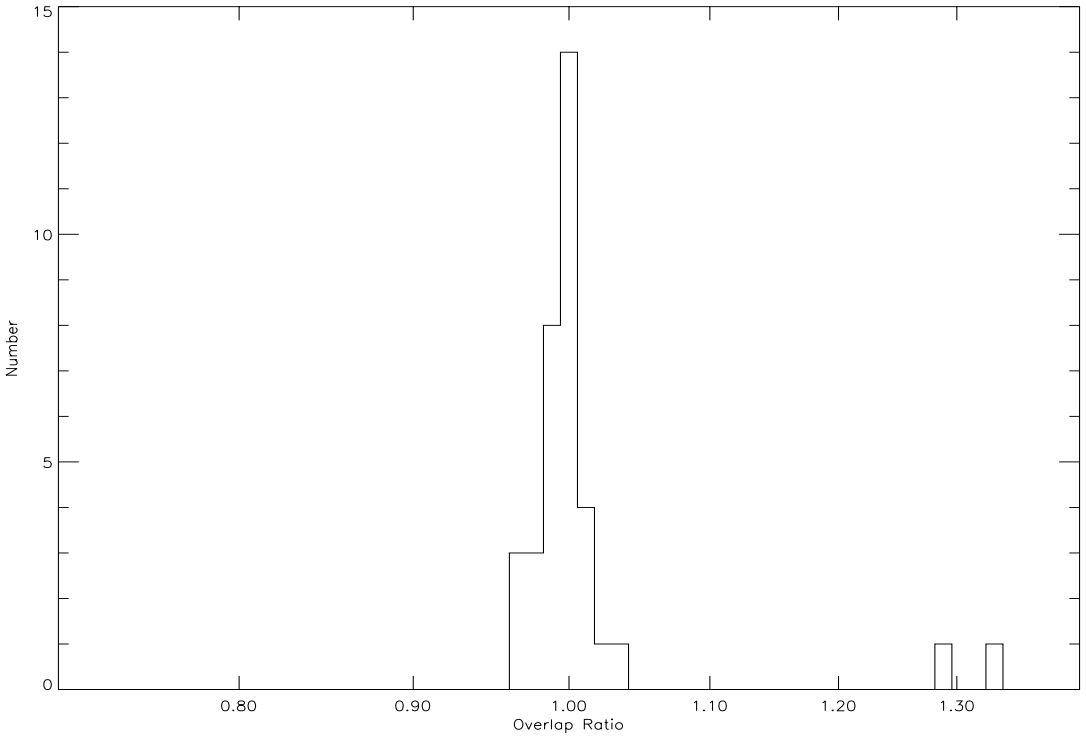


Figure 5. Grating overlap statistics for the Blue G130H and G190H observations of NGC 5548.



5. Comparison of AIS calibrated FOS data with NEWSIPS calibrated IUE data

Comparison of FOS and *IUE* UV spectra of three spectrophotometric standard stars (Colina & Bohlin 1994) shows that there is a difference of $\sim$6% between the absolute flux calibrations of the two instruments, with the FOS yielding larger measured fluxes. Their investigation shows further that the difference in the photometry is independent of wavelength. The differences between the photometric calibrations of the two instruments may arise from small differences between the white dwarf model temperatures used to fit the observed spectrophotometric standard star data.

Although comparison of standard star spectrophotometry is important because it allows us to evaluate the limiting photometric accuracies of the two instruments, such a comparison does not allow us to assess the photometric compatibility of the two archival databases for typical observations that often have poorer data quality than the standard star observations. The FOS standard star observations are not typical of all FOS observations because the former utlilize precision target acquisition sequences and the spectra have very high S/N ratios. To assess the differences between spectrophotometry that might be expected for more typical AGN observations, we have compared FOS and *IUE* spectra of three Seyfert galaxies with near-simultaneous (within 24 hours) observations. These observations are more representative of typical FOS archival data because "standard" target acquisition sequences are used, and the spectra have adequate but not outstanding S/N ratios. The FOS spectra were recalibrated with the *AIS* technique discussed above and the *IUE* spectra were calibrated using the NEWSIPS calibrations (Nichols & Linsky 1996). Details of the analysis can be found in Koratkar et al. (1997).

5.1. Wavelength comparison

We have shifted linearly the wavelength scale of the FOS grating data so as to place the interstellar absorption lines seen in these spectra at their rest vacuum wavelengths. This procedure is necessary because the FOS filter-grating wheel assembly is non-repeatable and can produce a shift in the wavelength zero-point. Since the interstellar lines are not well defined in the *IUE* spectra we have not applied any zero-point wavelength shifts to these data.

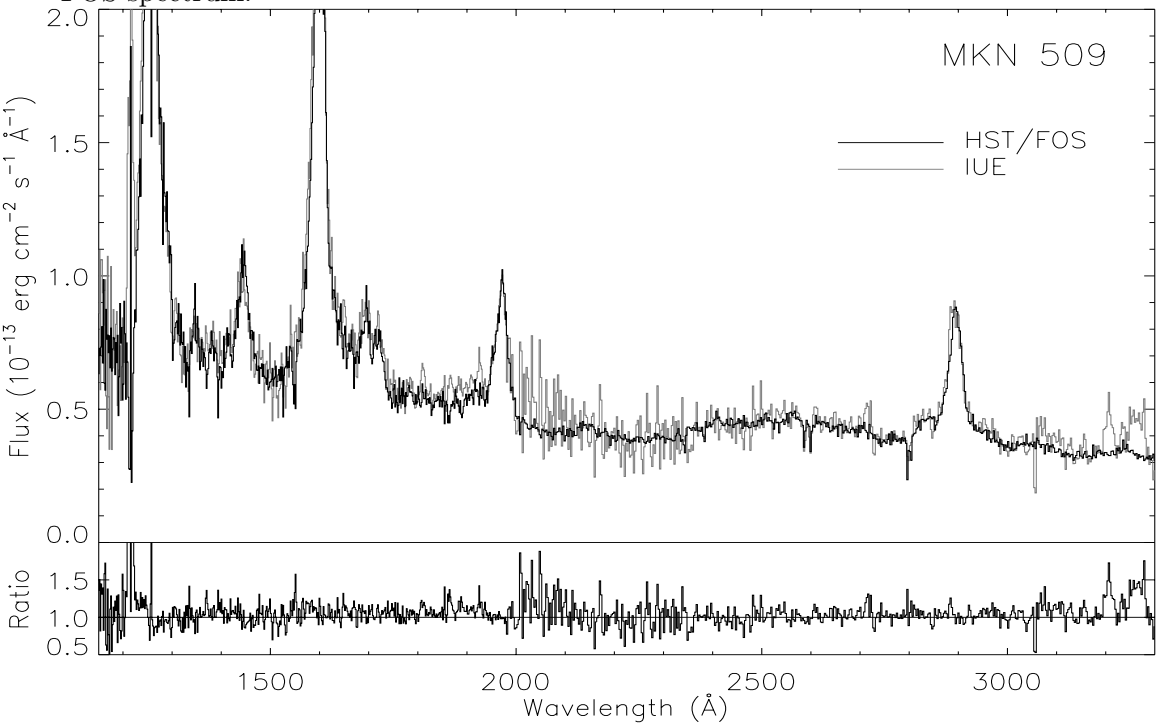
The wavelength calibration accuracy generally quoted for FOS spectrophotometry is 0.1 diode. This translates to a 1σ *FOS* wavelength calibration error of 0.1Å for the G130H grating, 0.15Å for the G190H grating, and 0.22Å for the G270H grating. Although the formal 1σ *IUE* wavelength calibration errors are $\sim$0.4Å for the SWP and $\sim$0.6Å for the LWP, the wavelength linearization solution can introduce non-Gaussian calibration errors of order 2–3Å in individual spectra.

Cross-correlating the strong emission lines visible in both the *FOS* and *IUE* spectra indicates that the wavelength calibrations of both instruments agree to within the errors expected for the *IUE* wavelength calibration. We therefore conclude that no zero-point shift or non-linear correction is required to align the *IUE* and FOS wavelength scales.

5.2. Photometric comparison

Figures 6, 7, and 8 compare the FOS and *IUE* spectra. In these figures, the recalibrated FOS spectra are resampled to the *IUE* wavelength grid and resolution. The figures demonstrate that the absolute photometric calibrations of the *FOS* and *IUE* show some differences, even for this limited set of observations. Globally, for MKN 509 and NGC 3783 the absolute photometry of the FOS and *IUE* agree within 5 ± 3%. A detailed inspection shows that this photometric agreement is independent of wavelength. Since the 1σ absolute flux calibration errors in FOS and *IUE* are 3% and 5% respectively, the photometric calibrations of

Figure 6. Comparison of the FOS and *IUE* spectra for Mkn 509. In this figure, the recalibrated FOS spectra are resampled to the *IUE* wavelength grid and resolution. The lower panel in the figure shows the ratio of the *IUE* spectrum to the FOS spectrum.



these observations are consistent with each other. However, for NGC 5548 the photometric differences are ∼50%.

For the spectra included in our comparison, the photometric calibrations do not produce the 6% larger apparent flux values for the FOS data seen in standard star spectra (Colina & Bohlin 1994). The photometric differences may be due to (1) inadequate aperture corrections, (2) target miscentering in the FOS aperture, or (3) non-linearity of the *IUE* flux scale. A detailed analysis of each of these effects (see Koratkar et al. 1997) indicates that non-linearity in the *IUE* detectors can account for most of the difference seen in the NGC 5548 data. Further, any one of the above effects by themselves or in combination could account easily for the negligibly small differences between the FOS and *IUE* absolute photometry of MKN 509 and NGC 3783.

5.3. Line measurements

The accuracy with which line fluxes can be measured depends strongly on both the ability to properly position the underlying continuum and on the ability to distinguish cleanly the line from the continuum. This in turn depends on both the spectral resolution and the S/N ratio of the data. For low S/N data, weak emission lines or emission-line complexes such as Fe II may artificially raise the continuum. Line measurements that employ profile fitting techniques can be affected adversely by low S/N and low spectral resolution, since the widths of the best fitting profiles increase as the resolution degrades and the weak lines become less well distinguished from the noisy continuum. Consequently, we should expect that for weak lines there may be significant differences between flux measurements from the FOS and *IUE* spectra. To quantify these effects, the intensities of a number of emission lines of different strengths are measured.

Figure 7. As Figure 6, except for NGC 3783.

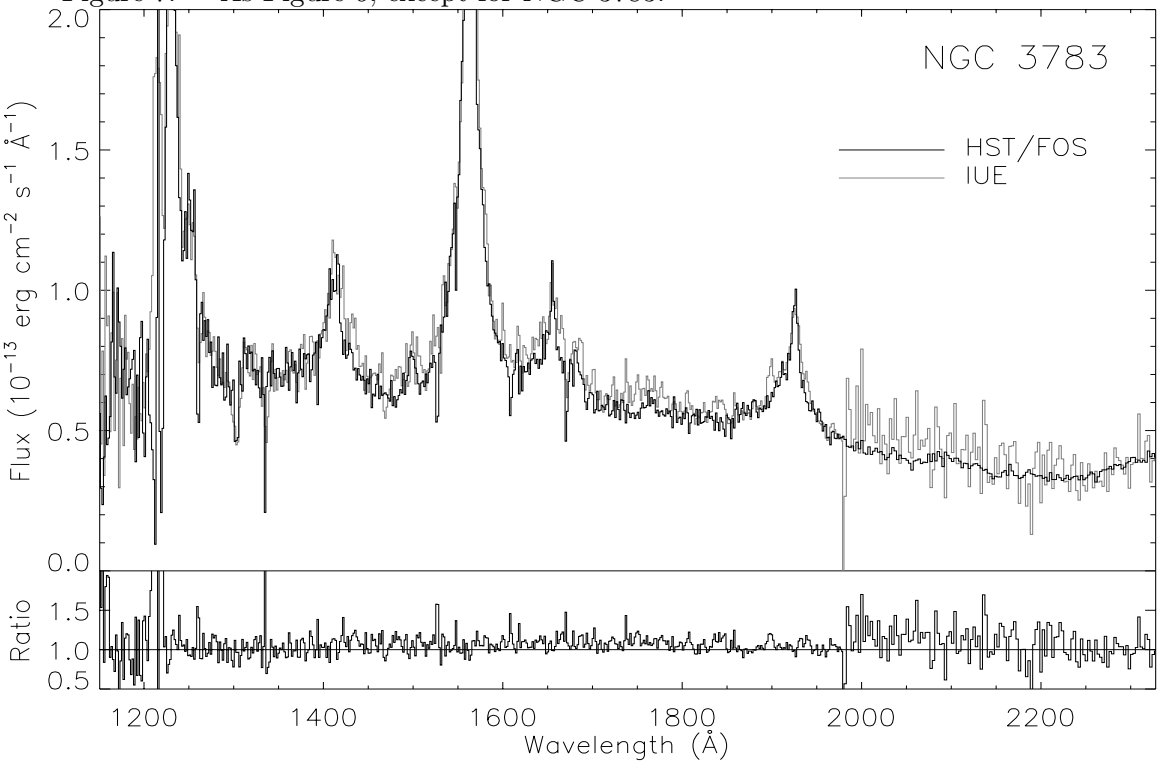
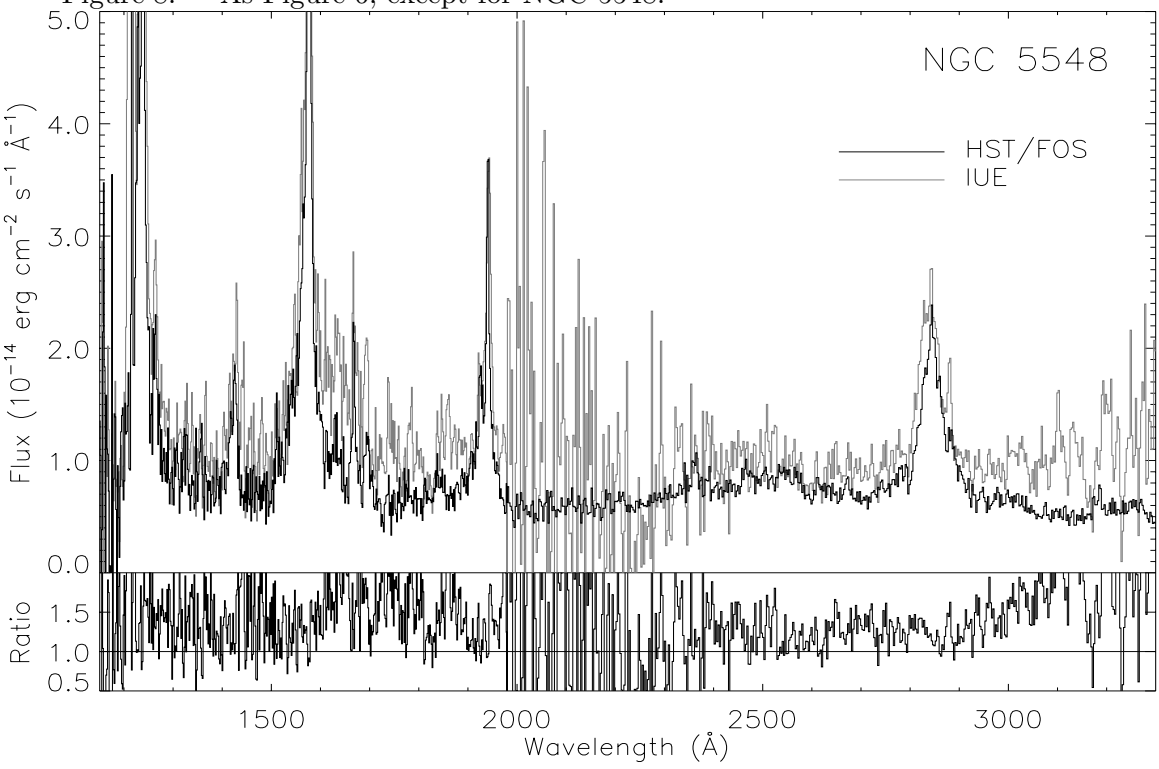


Figure 8. As Figure 6, except for NGC 5548.



A comparison of the emission line intensities show that the agreement between the line intensity measurements depends on the strength of the line. The strong emission lines such as Lyα and C IV agree to within 15%. Moderately strong lines (e.g., N V, Si IV/O IV, He II, and C III]) agree to within $\sim 30\%$ (1σ). When detected in the *IUE* spectra, weak lines (e.g., O I, C II, N IV], O III], N III]), could have disagreements as large as a factor of six.

6. Conclusions

Because of the changes in the calibration techniques over the life time of the FOS it is necessary to recalibrate archival data to obtain a consistent, uniformly calibrated sample. *AIS* recalibration of AGN spectra shows the expected dramatic rise in UV photometry because of the change in the photometric reference scale. The *AIS* calibration presently adopted for pre-COSTAR data improves significantly the photometric calibration of FOS spectra when compared to the previous calibration technique.

A complete set of recalibrated pre-COSTAR FOS AGN spectra will be published shortly in atlas form (Evans, Koratkar, & Pesto, 1998; Koratkar, Evans, Blitz, & Pesto, 1998), and will soon be available electronically also. We are in the process of recalibrating the complete set of post-COSTAR FOS AGN spectra.

A comparison of a limited set of FOS and *IUE* data shows that the photometric differences observed may be due to (1) inadequate aperture corrections, (2) target miscentering in the FOS aperture, or (3) non-linearity of the *IUE* flux scale.

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