Deployment of the COSTAR mirrors for GHRs has successfully cancelled the deleterious effects resulting from spherical aberration of the HST primary mirror. Prior to COSTAR, the Large Science Aperture (LSA) line spread function (LSF) was characterized by a Gaussian core nearly twice as broad as that provided by the instrumental resolution limit with extended non-Gaussian wings. After COSTAR the LSF for the LSA is only 20-30% broader in a Gaussian core than spectra from the SSA and the extended wings are absent.

I. Introduction

Prior to the deployment of COSTAR, observers with the GHRs were confronted with a difficult tradeoff when considering use of one of the two GHRs apertures. The 0.25 arcsec square Small Science Aperture (SSA) provided the full resolution expected with a narrow, clean Gaussian line spread function, but its transmittance was a factor of three lower than had been hoped. The larger 2.0 arcsec square LSA provided nearly the advertised (i.e., before launch) sensitivity, but its line spread function was seriously degraded (e.g., see GHRs ISR No. 55) by extended wings and by a Gaussian core that was twice as broad as hoped. The observer was required to accept either a large loss of throughput (SSA), or a substantial degradation of the LSF (LSA). Selection of an observing aperture required acceptance of a painful loss of either throughput or resolution.

After the deployment of COSTAR deciding which aperture to use for a given project may still be a difficult choice, but the drawbacks of each aperture relative to the other are now much less severe. The SSA throughput relative to that for the LSA after COSTAR ranges from about 0.5 to 0.7 from the far to near UV range of the GHRs. The LSF for the LSA is now nearly Gaussian and only 20-30% broader than that for the SSA. The tradeoffs between using the SSA and LSA are thus more subtle post-COSTAR.

The large effect of spherical aberration made characterization of the differential LSA to SSA LSF a relatively easy computation. Following deployment of COSTAR the LSA and SSA line spread functions are more similar; hence characterization of the differential LSF is a more subtle problem. In this report I will present results of directly solving for

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1 Copies of this report may be obtained from the Science Instruments Branch, Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.
the LSA to SSA differential LSF (see GHRS ISR No. 55 for details of the technique) and also discuss direct measures of both SSA and LSA spectral resolving powers based on autocorrelation analyses. Discussion of SSA throughput post-COSTAR will also be provided.

II. The GHRS LSF Observations.

As in two previous calibration programs the sharp lined star $\chi$ Lupi has been observed with both the SSA and LSA to provide LSFs at 1360, 1900 and 2680Å for the relevant ranges of G160M, G200M, G270M and ECH.B. Spectra to a $S/N$ of about 100 per quarter diode (pixel) were obtained at six different wavelength and element combinations. One wavelength setting was lost due to a carrousel lock failure with the GHRS. Table 1 lists the observation names and characteristics for the data obtained 17 February 1994.

<table>
<thead>
<tr>
<th>Rootname</th>
<th>Aperture</th>
<th>Grating</th>
<th>Wavelength</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>z28h0108</td>
<td>LSA</td>
<td>ECH.B</td>
<td>2682.0</td>
<td></td>
</tr>
<tr>
<td>z28h0109</td>
<td>LSA</td>
<td>ECH.B</td>
<td>1910.0</td>
<td></td>
</tr>
<tr>
<td>z28h010b</td>
<td>LSA</td>
<td>G270M</td>
<td>2688.0</td>
<td></td>
</tr>
<tr>
<td>z28h010d</td>
<td>LSA</td>
<td>G200M</td>
<td>1900.0</td>
<td></td>
</tr>
<tr>
<td>z28h010f</td>
<td>LSA</td>
<td>G160M</td>
<td>1900.0</td>
<td></td>
</tr>
<tr>
<td>z28h010g</td>
<td>LSA</td>
<td>G160M</td>
<td>1300.5</td>
<td></td>
</tr>
<tr>
<td>z28h010l</td>
<td>SSA</td>
<td>ECH.B</td>
<td>2682.0</td>
<td></td>
</tr>
<tr>
<td>z28h010m</td>
<td>SSA</td>
<td>ECH.B</td>
<td>1910.0</td>
<td></td>
</tr>
<tr>
<td>z28h010o</td>
<td>SSA</td>
<td>G270M</td>
<td>2688.0</td>
<td>LOST</td>
</tr>
<tr>
<td>z28h010q</td>
<td>SSA</td>
<td>G200M</td>
<td>1900.0</td>
<td></td>
</tr>
<tr>
<td>z28h010s</td>
<td>SSA</td>
<td>G160M</td>
<td>1900.0</td>
<td></td>
</tr>
<tr>
<td>z28h010t</td>
<td>SSA</td>
<td>G160M</td>
<td>1300.5</td>
<td></td>
</tr>
</tbody>
</table>

Exposure times required to reach a $S/N$ of about 100 ranged from 102s for the G270M LSA to 2450s for ECH.B at 1910Å with the SSA. All observations were obtained with FP-SPLIT = FOUR and processed to remove fixed-pattern noise from the final merged spectra.

It should be noted that $\chi$ Lupi is a double-lined spectroscopic binary with a 15.25 day period (Dworetsky 1972). With $K = 136$ km/s for the radial velocity amplitude separation of the two components, the rate at which the A and B spectra relative separation changes reaches about 2.3 km/s per hour at the time of most rapid change. Paired spectra through the LSA and SSA were acquired with time separations of 3.5 (ECH-B at 2682Å) to 5.5 hours (G160M at 1360Å). The 17 February 1994 data were acquired near the epoch of maximum change rate for the separate spectral components. Over the 4.5 hours separating the LSA and SSA ECH.B spectra at 1910Å the relative offset of A and B
spectra of \( \chi \) Lupi amounts to 7.4 km/s, or about two spectral resolution elements. With the B component contributing about 5-10% of the system light at 1910Å this results in minor intrinsic differences of the paired LSA and SSA spectra unrelated to the sought-after differential blurring. The intrinsic difference is not, however, systematic and a stable (though slightly noisier) solution for the differential LSF may be reached.

That the binary nature of \( \chi \) Lupi has not adversely affected derived LSFs has been verified via two different approaches: 1) There were two Cycle 3 executions of a similar LSF test; one was conducted near minimal rate of spectral component separation while the other was near maximal relative separation rate. LSFs derived from the two cases were not substantially different. 2) Detailed simulations have been performed to model the effect of a shifting binary component spectrum between the LSA and SSA exposures. These simulations consistently show that the minor spectral changes resulting from a few hour gap between the LSA and SSA spectra do not adversely affect the derived differential LSF, even though the residuals of LSA - LSF\( \times \)SSA are increased.

### III. Differential LSA to SSA Line Spread Functions.

Figures 1 and 2 illustrate the LSF solution for the specific case of ECHL 2682Å paired spectra. The differential LSF is shown (top panel of Fig. 1) that when convolved with the SSA spectrum (bottom panel Fig. 1) provides a best match to the observed LSA spectrum (top panel of Fig. 2). Figure 2 also shows the LSF\( \times \)SSA spectrum (i.e., convolution) and the difference (bottom panel) between this and the directly observed LSA spectrum. The differences in this case are indicative of some real changes to the spectrum over the five hours separating the SSA and LSA observations. Although the intrinsic spectrum changes contribute to an increased noise level, they are not systematic with respect to line characteristics and do not adversely influence the LSF and resolution determinations. It is worth pointing out that the LSF solution was constrained to be non-negative everywhere; a solution allowing negative numbers would appear little different in the core, but would have negative fluctuations at a level up to a few percent (without providing a significantly better fit).

Several simulations have been performed to test how well this approach extracts the differential LSF. The simplest case is simply to take an observed SSA spectrum and blur it by convolution with a narrow Gaussian to create a simulated LSA spectrum; done without adding noise to the simulated LSA spectrum the derived LSF perfectly matches the Gaussian used in the simulation. A more realistic simulation involves adding Poisson noise at about the 1% level to the simulated LSA spectrum, in this case an LSF is derived that again matches the input Gaussian quite well, but fluctuations in the LSF wings occur at the level of 1-2%. From comparison with simulation results the derived differential LSFs are indistinguishable from narrow Gaussians that simply broaden the resulting spectrum by some 20-30%. (An exception to this occurs for the far UV observation at 1360Å where a slight non-Gaussian wing may be present. This would be consistent with
the PSF degradation seen in the far UV with the FOC.) For the LSF shown in Fig. 1 the FWHM = 2.4 pixels; the resolution element of the instrument is about 3.7 pixels (Gilliland et al. 1992) for illumination of the SSA by a point source. For convolutions of two Gaussians the widths add quadratically. In the Fig. 1 case the resulting LSA resolution is $(3.7^2 + 2.4^2)^{1/2} = 4.4$ pixels, or 19% broader than the SSA case.

An autocorrelation of a spectrum may be used to measure typical widths of features in a spectrum. The autocorrelation $ac_j$ is defined over lags of ±15 pixels by evaluating the following for $j = 1$ to 31:

$$ac_j = \sum_{i=1}^{N} (sp_i - \bar{sp})(sp_{i+j-16} - \bar{sp})$$  \hspace{1cm} (1)

where $sp_i$ indicates a spectrum to be operated on over some domain $i = 1, N$, $\bar{sp}$ indicates the mean of the spectrum over the relevant domain. $ac_j$ is later normalized to have a value of unity at zero lag. Figure 3 shows the autocorrelations over 2686.7 - 2687.8Å of the ECHLB spectrum. This restricted domain was selected as having several lines that even at the Echelle resolution are close to being unresolved. The panels from left to right are for the SSA, LSA and LSF × SSA spectra. The curves show the autocorrelation, while the symbols show a Gaussian fit to the central core (± pixels of center). The Gaussian fit widths of the autocorrelation functions shown in Figure 3 are 4.63, 5.05 and 5.10 pixels for the SSA, LSA and LSF × SSA cases. For contrast with pre-COSTAR conditions Figure 4 shows autocorrelations over the same spectral domains for data from 15 January 1993. Not only is the LSF core for the LSA much sharper post-COSTAR, but the broad wings, as evidenced by both the differential LSF of Figure 1 and the autocorrelation results, have effectively been removed.

Rather than presenting detailed plots for all of the spectral element – wavelength combinations, I will simply provide summary plots and tables. Figure 5 shows the differential LSFs solved for with post-COSTAR data. For contrast Figure 6 shows the same for pre-COSTAR data. Introduction of COSTAR has clearly resulted in a much improved LSF for the LSA. A simpler way to compare the differential LSFs before and after COSTAR is to tabulate what fraction of the LSF is contained in the central four pixels and the central maximum – this is done in Table 2. Also shown in Table 2 is the FWHM in pixels of the central LSF peak for the post-COSTAR cases (see Fig. 5) as well as the percent increase in Gaussian core width this corresponds to relative to the instrumental resolution of 3.7 pixels.
Table 2. LSF Summaries

<table>
<thead>
<tr>
<th>Element (wavelength)</th>
<th>Pre-COSTAR</th>
<th></th>
<th>Post-COSTAR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>peak</td>
<td>sum - 4</td>
<td>peak</td>
<td>sum - 4</td>
</tr>
<tr>
<td>ECH.B (1900)</td>
<td>0.150</td>
<td>0.517</td>
<td>0.302</td>
<td>0.819</td>
</tr>
<tr>
<td>ECH.B (2680)</td>
<td>0.146</td>
<td>0.501</td>
<td>0.382</td>
<td>0.920</td>
</tr>
<tr>
<td>G160M (1360)</td>
<td>0.140</td>
<td>0.456</td>
<td>0.287</td>
<td>0.724</td>
</tr>
<tr>
<td>G160M (1900)</td>
<td>0.155</td>
<td>0.483</td>
<td>0.278</td>
<td>0.778</td>
</tr>
<tr>
<td>G200M (1900)</td>
<td>0.150</td>
<td>0.489</td>
<td>0.357</td>
<td>0.783</td>
</tr>
<tr>
<td>G270M (2680)</td>
<td>0.154</td>
<td>0.480</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

The autocorrelation widths of SSA and LSA spectra from two pre-COSTAR observation sets (DOY 015 = 15 Jan '93 and 050 = 19 Feb '93) are compared with the same from post-COSTAR data in Table 3. The tabulated widths refer to a Gaussian width from fitting to the central 11 pixels of the autocorrelations; FWHM of the function is 1.66 times the tabulated width. The autocorrelation width is typically larger than the intrinsic resolution limit due to contributions from resolved lines (Echelle mode) and blended features (first order spectra); the relative difference of LSA and SSA values pre- and post-COSTAR reflect the much improved LSFs.

Table 3. Autocorrelation Widths

<table>
<thead>
<tr>
<th>Element (wavelength)</th>
<th>pre-COSTAR (015)</th>
<th>pre-COSTAR (050)</th>
<th>post-COSTAR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SSA</td>
<td>LSA</td>
<td>SSA</td>
</tr>
<tr>
<td>ECH.B (1900)</td>
<td>4.76</td>
<td>8.18</td>
<td>5.08</td>
</tr>
<tr>
<td>ECH.B (2680)</td>
<td>4.02</td>
<td>7.61</td>
<td>3.58</td>
</tr>
<tr>
<td>G160M (1900)</td>
<td>4.04</td>
<td>7.32</td>
<td>–</td>
</tr>
<tr>
<td>G200M (1900)</td>
<td>–</td>
<td>–</td>
<td>3.94</td>
</tr>
<tr>
<td>G270M (2680)</td>
<td>3.74</td>
<td>7.30</td>
<td>–</td>
</tr>
</tbody>
</table>

IV. Consideration of SSA throughput post-COSTAR.

An important remaining issue for GHRS operations post-COSTAR is whether:

1. The COSTAR corrected throughputs and resolutions are as good as expected, and

2. could additional adjustments of the COSTAR mirrors provide improvements (if so, how much).

Pre-COSTAR the relative throughputs of the SSA to LSA ranged from about 0.25 to 0.35 from the far to near UV with well-centered targets. Post-COSTAR (Feb - March 1994
data sets) the SSA/LSA ratio varies from about 0.5 to 0.7 over the far to near UV - a typical gain of a factor of two in throughput ratio is obtained. The SSA throughput gain is about 20% lower than expected on average. It may be instructive to examine FOC “aperture” transmissions as a function of wavelength for comparison with the GHRS results. FOC encircled energy fractions post-COSTAR may be found in Table 8 of the FOC Instrument Handbook (V 5.0, Nota 1994). Table 5 shows FOC throughputs for a 0.121” radius aperture (same size as the GHRS SSA), predicted GHRS transmittances for the SSA, LSA and derived SSA/LSA ratio (from G. Hartig 1994 based on CODE V/TIM modeling), and as observed SSA/LSA ratios.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>FOC (0.121)</th>
<th>SSA</th>
<th>LSA</th>
<th>SSA/LSA</th>
<th>SSA/LSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>0.56</td>
<td>0.64</td>
<td>0.92</td>
<td>0.70</td>
<td>0.49</td>
</tr>
<tr>
<td>1500</td>
<td>0.67</td>
<td>0.69</td>
<td>0.94</td>
<td>0.74</td>
<td>0.55</td>
</tr>
<tr>
<td>2000</td>
<td>0.77</td>
<td>0.74</td>
<td>0.96</td>
<td>0.77</td>
<td>0.58</td>
</tr>
<tr>
<td>3000</td>
<td>0.84</td>
<td>0.84</td>
<td>0.97</td>
<td>0.81</td>
<td>0.70</td>
</tr>
</tbody>
</table>

*Measured encircled energy of COSTAR corrected F/96 mode for a radius of 0.121” relative to 1” radius encircled energy to approximately match the GHRS SSA/LSA ratio.

b Predicted (G. Hartig 1994) throughputs based on CODE V/TIM models.

c Observed SSA/LSA ratio with post-COSTAR GHRS.

It should be noted that the FOC encircled energy is derived as a ratio to the energy within 1” radius. Since the area of a 1” circle is nearly identical to the GHRS LSA size the quoted FOC small “aperture” throughputs may be compared directly to the SSA/LSA ratio. Comparing the observed FOC and GHRS results (second and last columns) suggests less than a 20% throughput deficit for the SSA nearly independent of wavelength. The observed SSA/LSA ratio is sensitive to the precise centering of the target in the SSA. Some component of the 20% deficit could result from imperfect centering in the SSA. (A systematic offset is possible if the centering that maximizes throughput for the mirrors which are used for acquisitions does not also maximize throughput for the dispersing elements. The mirrors and dispersers sample different parts of the beam thus making plausible a minor offset.)

It should be noted that SSA/LSA ratios of 0.63 at 1500 Å were measured during COSTAR alignment activities, but values consistently below this have followed for post-alignment observations.
V. Discussion.

Aspects of the LSA line spread function after COSTAR correction have been discussed based on analyses of an SMOV program to observe the sharp-lined star \( \chi \) Lupi through both the LSA and the SSA. Unlike the grossly distorted LSF of the LSA pre-COSTAR, the version after COSTAR correction is not easy to quantify in detail. The post-COSTAR LSFs of the LSA are matched reasonably well by a simple Gaussian about 20-30\% broader than the one diode resolution element as provided by the SSA.

REFERENCES

Dworetsky, M.M. 1972, PASP, 84, 254
FIGURE CAPTIONS

Fig. 1. Differential LSF solution for ECH.B data at 2682Å from 17 Feb '94 is shown in the upper panel. Lower panel shows the observed SSA spectrum.

Fig. 2. Upper panel shows the observed LSA spectrum of 17 Feb '94. The middle panel shows the SSA spectrum after convolution with the LSF which should closely reproduce the LSA observations. Bottom panel is the difference spectrum.

Fig. 3. Autocorrelation functions (smooth curve) and Gaussian fit to cores (‘+’) for a restricted domain (see text) of the ECH.B spectra shown in Figures 1 and 2.

Fig. 4. Same as for Fig. 3, but for pre-COSTAR spectra, note little change of SSA case and large change for the LSA.

Fig. 5. Differential LSF solutions after COSTAR correction for the spectral element–wavelength cases presented in Table 1.

Fig. 6. Same as Fig. 5, but for pre-COSTAR data, note the lower central peaks, broader core and extended wings.
Fig. 1
Fig. 2
Fig. 3
Fig. 6