DECONVOLUTION OF SIMULATED HST SPECTRA

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With the poor focus of the HST OTA, observations through any but the smallest spectrograph apertures will suffer a loss of spectral resolution. We provide here a preliminary discussion of deconvolution of spectra obtained through the large aperture of GHRS. The throughput of the 0.25" SSA is expected to be a factor of four (perhaps a greater factor in the UV where GHRS operates) smaller than that for the LSA. Given the expected factor of two greater S/N for equal length observations obtained through the LSA, the possibility of using deconvolution to restore resolving power at the high S/N is enticing. There are two primary parameters characterizing observed spectra that need to be explored in terms of effectiveness of deconvolution: 1) S/N of desired spectrum, 2) width of spectral features relative to intrinsic resolving power of the spectrograph. The relative effectiveness of deconvolution is a weak function of the S/N to be obtained. For input spectra that have very sharp features, unresolved by the spectrograph, observations with the SSA remain better than deconvolved LSA spectra, if the full resolution is desired. For input spectra with broad features that are well sampled by the spectrograph, the higher S/N of the LSA observations produce superior results to observations (same exposure time assumed) through the SSA. Deconvolution can provide important gains for the analysis of GHRS spectra obtained through the LSA. The choice of aperture selection, and hence exposure time to reach a given S/N, depends on details of the spectrum to be observed, thus consideration of deconvolution does not provide a universal argument of how to structure an observing program.

Consideration is also given to added complications that may arise with FOS spectra, these are not in general serious deviations from GHRS results.
I. INTRODUCTION

Recent analysis of OTA focus problems has shown that a significant component of spherical aberration will remain in the HST mirror system. This results in a spatial point spread function (PSF) that is about a factor of 5 broader for 70% encircled energy than expected. It is the purpose of this report to address the extent to which deconvolution of the spatial smearing can be used to restore the inherent spectrograph resolving power. There will be many subtleties that can not be addressed in this report, in particular deconvolution processes are sensitive to the noise characteristics that are not simulated in detail here. It should be emphasized that this report is based on quite preliminary information, the final focus of HST for use by GHRS has not been empirically determined at this time.

The choice of slit width to be used in obtaining spectra is a common problem for both ground and space based spectroscopy. Selection of a narrow slit allows the full resolving power of a spectrograph to be obtained, but results in loss of sensitivity. A wide slit allows full sensitivity, but at the expense of lost resolution. The HST spectrographs (GHRS and FOS) have selectable aperture sizes. For the GHRS the 0.25" and 2.0" slit widths (square apertures) were expected to yield comparable resolving powers for spatial point sources, since most of the light was to have been concentrated in the smaller aperture. Use of the 2.0" LSA would have resulted in loss of spectral resolving power only if the source had real spatial extent. With the much broader PSF now expected, observations through the LSA will suffer a factor of 2 to 3 loss of resolution. Consideration of which aperture to be used is now more complicated. An important difference of wide slit HST spectroscopy versus similar approaches on the ground should be explicitly noted: Use of a wide slit for ground based observations results in lost spectral resolution from both seeing and image motion variations of the spatial input function; the time averaged PSF cannot be recovered under typical observing setups. On HST the resolution is lost only due to the broader spatial PSF; it is not expected that image motion will contribute in any significant way to the broadening. Furthermore, with the GHRS, it is possible to directly map the spatial distribution of light falling on the apertures. Excellent knowledge of the spatial PSF, degrading observations with wide slits, makes the application of deconvolution of this smearing much more favorable than for most ground applications.

We discuss in the next section simple experiments to test deconvolution of simulated GHRS data.
II. DECONVOLUTION OF GHRS SPECTRA

We assume in most of the following that the spatial point spread function is an exactly known quantity. In practice it is likely that the PSF will be a function of wave length, and that a substantial calibration effort will be required to characterize it. The assumption of a known PSF is probably not a very serious limitation of the current study. More importantly, we assume that the only noise source is simple counting statistics. In practice the GHRS data will have residual flat-field errors that could seriously complicate the deconvolution issue. The results of this memo are of course sensitive to the exact nature of the UV PSF. We have adopted here the spatial PSF as seen with 14 June 1990 PC observations; this PSF has the most light within a 0.25" diameter aperture of any to date. Should the relative distribution of light in the UV be significantly different (e.g. further factor of two drop of relative SSA and LSA throughput), then the conclusions of this work would in some cases change.

We adopt a very simple test approach:

1. Generate a spectrum with several randomly positioned lines and a continuum by simply summing a constant and several gaussians to represent the lines.

2. Produce spectra as would be seen through both the SSA and LSA by convolution of the input spectrum with the assumed spatial PSF. This automatically scales the throughput and degrades the resolution.

3. Add in Gaussian noise with a variance equal to the local intensity for both the SSA and LSA spectra separately.

4. Using the assumed spatial PSF deconvolve the spectra.

5. Compare how well the deconvolved LSA and SSA spectra reproduce the input spectrum.

The above tests are repeated as a function of input S/N, absorption versus emission line features, width of lines relative to spectrograph resolution limit, and first order versus Echelle A (different internal demagnifications).

We follow the approach to deconvolution as discussed in Numerical Recipes (Press, et al. 1986) section 12.6. The choice of an optimal (Wiener) filtering with use of FFTs, simultaneously provides a very efficient solution, with a constraint that the deconvolved spectra represent the true signal as well as possible in the least-squares sense. This approach suppresses the highest frequencies in the Fourier transform, thus automatically applying a low pass filter operation. The inherent S/N and width of input spectral features determine the precise optimal filter to be used. Since we have used simulations, we know precisely the signal and noise characteristics, and therefore can specify without assumptions
the proper optimal filter. In practice the correct filter must be determined as a
function of the observation, this is not likely to be a serious problem; the results
are not overly sensitive to details of this filter.

(Dennis Ebbets and Don Lindler of the GHRS team gave a discussion of "En-
hancement of Data from the High Resolution Spectrograph" using an iterative,
constrained algebraic approach - BAAS, 19, 747, 1987. Their work was aimed
at obtaining "super resolution" by deconvolution of the spectrograph line spread
function to obtain more than nominal resolution for cases in which the input
spectrum is known to be unresolved. This study has the different goal of de-
convolving the effects of an extended spatial PSF to recover nominal resolving
power. The optimal filtering approach could be applied to the case studied by
Ebbets and Lindler; a quick test of this showed reasonable results. The FFT
approach is much faster, requiring only a fraction of a second on a SUN Sparc-
station to deconvolve a 2000 point spectrum, while the approach of Ebbets and
Lindler took about two hours of VAX 8200 time. A further comparison of the
two techniques with different motivations is beyond the scope of this study.)

We note that the simulated spectra to be discussed here are not intended to
represent any particular astrophysical targets. The important quantities for us
are as explicitly noted, examples of objects that might yield similar spectra range
over many stellar magnitudes (about 0th to 18th in different cases).

Figure 1 shows results for a specific test case, with the perfect input spectrum
shown in the upper panel; lower panels show results of convolving with the SSA
and LSA smearing functions with noise added. The loss of throughput and
spectral resolution are easily noted. Figure 2 shows the results of deconvolution;
the original resolution is nicely recovered, as are intensities of the spectral lines.
The optimal filtering deconvolution results in a noisier continuum, and thus
lower S/N for the LSA case in which more resolution restoration was required.
Thus, although the SSA spectrum contains nearly a factor of four fewer counts,
than the LSA case, upon restoration the SSA has a better S/N. Figure 3 shows
the differences of deconvolved spectra relative to the noiseless input function.
While the SSA spectrum exhibits a higher general S/N, the LSA spectrum may
do a slightly superior job of precisely reproducing line structures. The results
do not show a strong preference for selecting one aperture over the other for this
case of observing very sharp spectral features. We present in Table I a summary
of this experiment conducted with S/N as the only variable. The columns in the
table represent respectively: S/N of spectrum through LSA, rms of continuum
region after deconvolution for LSA, rms of continuum after deconvolution for
SSA, fraction of Fourier space frequencies retained in the optimal filtering.
TABLE I. Deconvolution performance vs. S/N

<table>
<thead>
<tr>
<th>S/N(L)</th>
<th>rms(L)</th>
<th>rms(S)</th>
<th>frac</th>
</tr>
</thead>
<tbody>
<tr>
<td>310</td>
<td>1460</td>
<td>888</td>
<td>.373</td>
</tr>
<tr>
<td>155</td>
<td>590</td>
<td>395</td>
<td>.324</td>
</tr>
<tr>
<td>77</td>
<td>233</td>
<td>170</td>
<td>.265</td>
</tr>
<tr>
<td>39</td>
<td>87</td>
<td>70</td>
<td>.199</td>
</tr>
<tr>
<td>19</td>
<td>29</td>
<td>27</td>
<td>.126</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>9</td>
<td>.064</td>
</tr>
</tbody>
</table>

The table illustrates the general tendency for deconvolution of the LSA spectrum to have more amplified noise. Only at the lowest S/N does the deconvolved noise in LSA perform as well as that for the SSA.

A strict repeat of the above test using absorption lines showed no discernible difference with respect to the emission line case.

The next set of results are for spectra that are dominated by crowded absorption features, but of different intrinsic width. Figure 4 shows a perfect input spectrum composed of 200 randomly spaced absorption features, and its convolution through the SSA and LSA. As before the loss of throughput and resolution are quite noticeable. Figure 5 shows the deconvolved spectra for this case of sharp input spectral features, and Figure 6 shows the difference spectra. Figures 7 and 8 show the input spectra and differences for 50 randomly positioned lines, with intrinsic widths of eight times the instrumental resolution limit. The following table summarizes results for the three absorption line simulations.

TABLE II. Absorption line spectra deconvolutions

<table>
<thead>
<tr>
<th>no. lines</th>
<th>width</th>
<th>rms(L)</th>
<th>rms(S)</th>
<th>frac</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>1</td>
<td>313.</td>
<td>202.</td>
<td>.35</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>177.</td>
<td>117.</td>
<td>.21</td>
</tr>
<tr>
<td>50</td>
<td>8</td>
<td>45.</td>
<td>60.</td>
<td>.07</td>
</tr>
</tbody>
</table>

Clearly the small science aperture produces better results where the spectrum contains information at resolution close to the instrumental limit. If the lines are well resolved, observing with the LSA is likely to provide the best results.

A final complication to be pursued in the analysis of gains to be provided with deconvolution for the GHRS is the internal demagnification difference between first order gratings and the Echelles. In particular the slit widths in Echelle A (Echelle B case is intermediate) project to only 66% the width for the first order grating cases studied earlier in this report. Thus the throughput differences between the SSA and LSA remain the same, but loss of resolution in the LSA
is decreased. As a test case we repeat the absorption line spectrum case with 100 lines at a width of twice the instrumental resolution, at the resolution loss appropriate to Echelle A. The rms for deconvolution of the LSA case drops from 177 (line 2 of Table II) to 139 in this case, thus improving as would be expected, but remaining a little poorer than the SSA case.

The simple deconvolution tests described above suggest that the relative performance of the SSA and LSA remain much as expected (for point sources) were the OTA image as specified. With original expectations the SSA and LSA would have produced minor differences of throughput and resolution for point sources. Now the throughputs and resolutions are quite different, but after application of deconvolution to restore resolution for the LSA observations, S/N is similar to that obtained in equal time to SSA observations. In this sense it is fair to claim that the impact of the degraded PSF is simply gauged by the loss of throughput for the SSA. For observations in which the spectral line information is well sampled the LSA can provide good results at less degradation.

Complications for deconvolution of FOS data Although quite similar in terms of slit sizes, and detector systems the FOS presents significantly greater problems for use of deconvolution techniques. In particular, at the low resolutions of FOS, observations are made over a significant (sometimes all) fraction of the free spectral range of a grating or prism. Near the ends of a gratings free spectral range the internal line spread function deviates from a clean gaussian, this occurs at perhaps the 20% level for FOS. Furthermore a given spectrum with FOS, spanning a large relative domain of wavelength is more likely to have a variable spatial PSF as a function of wavelength. The latter complication cannot be easily taken into account with direct Fourier domain deconvolution techniques. A variation of the smearing PSF over the spectral domain will produce sensitivity and resolving power variations through the spectrum. Presumably the sensitivity variation can be easily calibrated and corrected for.

Until the PSF is well characterized as a function of wavelength it is premature to devote much effort to studying how this problem might be dealt with in spectrum reconstruction. Since errors will inevitably be made in the characterization of the PSF, and given that this will produce problems of a similar nature to variability of the PSF along the spectrum, we produce a sensitivity estimate to incorrect setting of the PSF.

To make this test easier to conduct and interpret we assume that the spatial PSF can be represented as the sum of two gaussians over a large slit. We will produce a pure input spectrum as before. In the convolution step, to simulate the smearing induced by the broad PSF, we use two different PSFs, differing in relative contributions of the narrow and broad gaussian components. In the deconvolution step we will use response functions that are both too narrow, and too broad by order of 10%.

The deconvolutions suffer minor degradation when the PSF used for deconvolu-
tion does not match that used in generation of the simulation, but the effect is not major.

Another version of this test involved convolving the two halves of a spectrum with different PSFs, deconvolving the resulting spectrum twice, once with each PSF, then patching together the corresponding halves of the deconvolved spectra. This worked quite well, suggesting that the mild variation of PSF with wavelength expected in FOS spectra can be dealt with in this way with little loss.

SUMMARY

The results so far show that deconvolution can work quite well at restoring resolving power. However, for retention of maximum resolution and S/N it will in general be better to observe through the SSA, even with its extra factor of 4 light loss. There is a substantial noise penalty associated with deconvolution of the LSA data. For those programs that do not need the limiting resolution provided by the element in use may well benefit from use of a wider slit, with or without subsequent deconvolution. The deconvolutions described herein have used generally favorable assumptions (simple noise model, usually perfect knowledge of response functions, gaussian line profiles, smooth continuum), any use of more realistic assumptions would make the use of the SSA appear even more favorable. It remains to be seen whether other reconstruction techniques might work better, and possibly make the relative importance of LSA observations higher.