1D "CLEANing" of HST Spectra

(or, Converting Large Aperture Spectra to the Resolution of Small Aperture Spectra)

Steven V. Penton (spenton@colorado.edu), http://cos.colorado.edu,
Center for Astrophysics and Space Astronomy, University of Colorado at Boulder, USA

Motivation

Large aperture spectra provide greater signal, but small aperture spectra have higher resolution (smaller line-spread function (LSF) wings). What if you wanted the best of both—maximum flux and resolution—and wouldn't? The simple method presented here can convert large aperture spectra to the resolution of small aperture spectra by removing the wings of the LSF without significant noise being added to the continua. In addition, this method/algorithm allows spectra taken through different apertures to be placed upon a common baseline for increased signal-to-noise (S/N). In marginal S/N cases, such as QSO absorption studies, this method is a particularly promising archive mining tool.

Method

The method is inspired by the 2D 'CLEAN' method used in radio astronomy (Briggs, 1995), but adapted to 1D spectra. At the location of the highest flux point in the spectrum, a wavelength-dependent line-spread function (LSF) of photons is subtracted and its location stored. The LSF of photons subtracted is a small fraction (~10%) of the number of photons at this spectral location. Simultaneously, a new spectrum is created by adding a replacement LSF of photons at the original spectral location in the new spectrum. The replacement LSF could be a Gaussian of specified width, a delta-function, the LSF of another grating/combination, or any other LSF (such as a 'wings' approximation of the original or alternate LSF). Successive passes through the remainder spectrum result in a residual spectrum that, after many such passes, begins to resemble a featureless continuum. Features are trunched when the maximum remaining flux is a predetermined fraction of the original error vector; or, equivalently, when a certain size feature is no longer present in the spectrum. After this process has finished, a new spectrum is created by adding the remaining residual spectrum to the "cleaned" version.

Line-Spread Functions (LSFs)

The LSF describes the instrumental spectral distribution of an incident monochromatic emission source (delta-function) and is a function of aperture, grating, and wavelength. Sample STIS/STIS first-order MAMA LSFs are shown in Figure 1 (taken from the STIS instrument handbook). With increasing aperture size and photon energy, the percentage of flux in the wings of the LSF increases significantly. HST spectral observers are forced to consider the trade-offs between apertures, often sacrificing flux (signal-to-noise) for resolution. For example, even though the reported (integral) Parkes are nearly identical, 1203 Å Gunn observations were forced to select from apertures ranging from 4.2 to 9.1% transmissions and undocumented spectral resolution changes of greater than 10%.

Increased Resolution

Spectral resolution (R=λ/Δλ) is often defined by the half full width at half maximum (FWHM) of the spectral core. However, a core is a line-spread function (LSF) and is only achievable for delta-function absorption or emission (see "to quantify the achievable resolution for a realistic astrophysical situation, we performed simulations with identical 60 km/s absorption features of variable separation at 1216Å). We define the resolution R_{GW} as the separation between identical Gaussian absorption features at which the central maxima between the two maxima has a flux deficit of 50% of the feature maxima. Sample simulations for two separations are shown in Figure 1.

Marginal (1%) Increase in Continuum Noise

To examine the effects of our spectral cleaning on continuum noise, we "clean" a simulated S/N of 20 per pixel STIS/G140M spectrum (52x0.2" aperture) over a continuum of 200Å (4000 pixels). "Raw" resolution (no cleaning) of the input spectrum, containing photon noise only, was convolved with the 52x0.2" aperture LSF, then "cleaned" using a delta-function replacement. Figure 2 displays a histogram of the before and after continuum counts (left) and the differences (residuals, right) for a S/N of 20. With a S/N of 20, we are able to retrieve the convolution with a ±1σ error of 1.5 counts, or 13400 ± 3%. For a S/N of 10 spectrum (right panel), we are able to retrieve the continuum to within 0.2% in both examples. The continuum component of the residuals is 1% and is a small fraction (20%) of the intrinsic photon noise. Further optimization of our algorithm will only reduce this non-Gaussian noise component. The main point of this analysis is that even using the most extreme output LSF, a delta-function, the added non-Gaussian noise is quite small. This is, of course, a major concern since these non-Gaussian residuals could be misinterpreted as larger deviations and reclassified as real absorption or emission features.

Combing Spectra

At all level, all HST archival spectra should benefit from our spectral cleaning. However, of the 20,400 first-order STIS spectra in the archive, the "5140 (7%) that were taken with larger (≥ 0.7") apertures will benefit the most from our spectral cleaning due to the significant LSF wings. Once "cleaned," these larger aperture datasets can be combined with other "cleaned" observations of the same target taken through other apertures without spectral degradation to produce higher signal-to-noise (S/N). In other words, this method allows archive users to place observations taken through different apertures onto a common frame. In addition, the negative impact of non-Gaussian wings of the LSF can be removed, resulting in increased resolution with minimal contribution to continuum noise. Our algorithm works for all HST modes for which the LSF is well known.

Caveats

The algorithm only works if the LSF is well-known.

The algorithm is ONLY designed to correct non-Gaussian LSF wings. If the intrinsic LSF does contain significant wings (i.e., STIS/STIS echelle data), then this algorithm will not significantly improve the data except in the case of combining data taken with different apertures.

The algorithm is still under development and has not yet been applied to more than a couple of STIS echelle datasets. For now, if you consider this a promising, but unproven, calibration tool.

There are several subtle nuances of the algorithm (which do not affect the statistics) that are not revealed here.

Example

To demonstrate the operation of this algorithm we compare two spectral cleanings of HST/STIS/52x0.2"/Spectrograph (PG 0946+301) observations of the QSO PG 0946+301 (z=1.216) to the original spectrum and an HST/STIS/52x0.2"/G230L spectrum (Figure 3). The two cleaned spectra (the "wingless" 52x0.1" and delta-function replacements) show deeper absorption features, more like the HST/STIS/2300Å spectrum. In particular, narrow absorption features, such as Lyα at 1215Å and CIII] at 1909Å, are poorly reproduced by the normal STIS pipeline data reduction, but are recovered by our spectral cleaning, which looks very similar to the G230L spectrum degraded to the STIS/230L resolution.

Conclusions

By removing the non-Gaussian wings of the LSF, our algorithm increases the resolution of HST archive spectra by as much as 70% for the STIS medium resolution gratings, while introducing <1% noise to the continua. Our algorithm also allows spectra taken through different apertures to be combined in a way that actually increases the S/N and spectral resolution.