Calibrating Extended Sources with the IRS

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1 Introduction

Accurate flux calibration of extended sources has always proved a challenge for slit spectrographs (e.g. Salama, 2000), since uniform, beam-filling extended source astrophysical references of known flux intensity (in MJy/sr, for instance) as a function of wavelength are not generally available. Instead, stellar point sources with well-measured and/or modeled flux distributions are used to provide spectrophotometric reference. The flux-calibration of point sources is then (ideally at least) trivial — as long as all science targets are point sources, and are placed in exactly the same position within the slit as the reference calibration star(s), all details of beam acceptance profile and diffractive losses, which vary significantly with wavelength, precisely cancel out, and the ratio of unbiased spectra between target and calibration reference will form an accurate physical flux ratio with the model flux. This ideal situation, though approachable for point sources, is by definition not possible for extended sources, light from which enters the slit at all allowable angles. At present there are three main issues with extended source calibration which will be discussed in order of their ease of treatment.

2 Beam Profile

2.1 The Problem: Converting Fluxes to Intensities

Since light from extended sources completely fills the slit, an accurate measurement of the *beam profile*, which represents the acceptance throughput of the slit at all angles, is required for each slit. Assuming a completely unbiased estimate of the flux (in MJy) present in the full-slit spectrum of an extended source is available, conversion to a flux intensity (in MJy/sr) requires the two-dimensional integral of the beam profile, which describes the angular area on the sky which has contributed to the spectrum, weighted by the angle-dependent throughput.

2.2 The Solution: Estimate and Integrate the Beam Profile

The beam profile can be measured using finely stepped pointings of bright point sources which map out the slit; such focal-plane mapping data was obtained during IOC to define the IRS slits' centers and widths. An estimate of the point spread function can be convolved with a model of the beam profile, and compared to the measurements (preferably at several different wavelengths), iterating to find the best solution (e.g. Lloyd, 2003; Salama, 2000). Individual one-dimensional, cross-slit integrals of the beam-profile are also necessary to flux calibrate spatially-resolved pixels along the slit (for instance, in spectral mapping or long-slit spatial applications).

3 Losses from Extraction Methodology

3.1 The Problem: A Narrowing Aperture

To estimate the physical flux of a point source, you must first extract its spectrum, and compare that extraction to a calibration standard extracted *in precisely the same way.* The IRS pipeline has standardized on an extraction method tuned specifically to point sources. When extracting faint spectra, two motivating factors on the choice of aperture exist, and are at crossed purposes:

1. To keep the spectrum from being biased, you must *increase* the size of the extraction aperture at all wavelengths, to ensure no source photons are being *lost.*
2. To keep the signal-to-noise ratio high, you must *reduce* the size of the extraction aperture to avoid unnecessarily folding in noise from pixels containing only sky.

Since the point spread function delivered by the telescope+spectrograph combination is diffraction-limited and scales linearly with wavelength, it seems natural to specify an extraction aperture whose width also scales with wavelength. This was the choice made for the extractor built for the IRS pipeline. This is exactly analogous to the choices which must be made in the photometric calibration of imagers (like MIPS or IRAC): a large photometric radius ensures unbiased fluxes, but is unnecessarily noisy; a small radius preserves high S/N, but at the expense of photometric precision for large extraction apertures[1].

The extraction aperture expands with wavelength, but the wavelength center and pixel size are independent from order to order; for instance, in Short-Low, Order 1, the aperture is 4 pixels at $14\,\mu$m, expanding with wavelength from 2.16 to 4.39 pixels along the order (see Fig. 1). Though it scales with wavelength, unless the exact PSF delivered were well-known, such an expanding aperture necessarily excludes a changing fraction of the target flux as a function of wavelength. This is not a problem in and of itself. As long as all science targets are point sources, are placed in exactly the same position in the slit (or have the aperture centered on them in exactly the same way as the reference calibrator did), the effects will cancel out. However, if the point source is not well centered in the aperture, or if an extended source is extracted, order to order mismatches will occur, as in the "straight-sided" extraction of calibration star HR6348 in Fig. 2.

The details of the extraction are actually folded into the pipeline in several places. The `FLUXCON` tables, which specify the per-order flux conversion from e/s to Jy, modulated by tuning coefficients to recover any wavelength dependence, obviously depend on the method of extraction. A less obvious way the extraction aperture may enter is through the flat fields. Since stars are used to create the flat-fields by dithering across the slit, and the spectral shape of the star must be removed from the

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[1] Both of these cases have similar solutions which sidestep the conflicting needs which trade between unbiased measurements and high signal-to-noise measurements: for images, PSF-fitting photometry, and for spectra, optimal extraction ensure that all the light is captured, but noisy pixels are weighted less, such that they don't overly reduce the S/N.

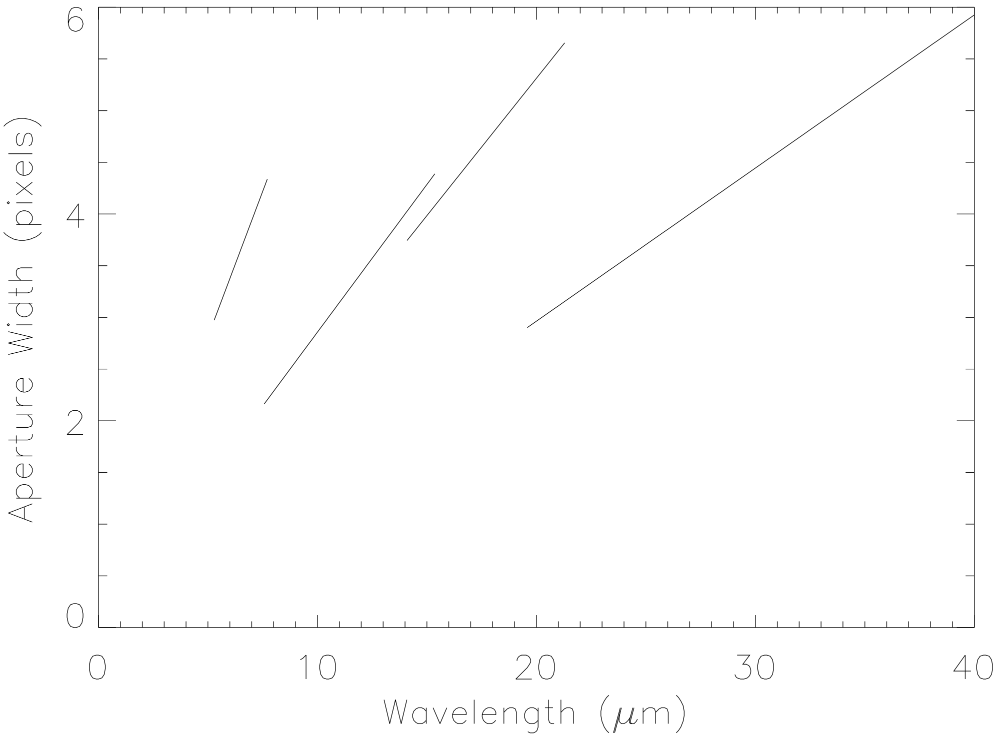

Figure 1: The aperture width for (left to right) SL2, SL1, LL2, and LL1 as a function of wavelength. Note the disparity between aperture widths at the wavelengths of order overlap.

true instrumental variations, the effects of narrowing extraction are folded in. Newer flats are made with very finely stepped stellar spectra, and flux *models* instead of extractions, and should be immune to this effect. The entirety of the aperture loss effect is then confined to the `FLUXCON` tables.

Only stars extracted using the same type of aperture, exactly replicating the fraction of flux discarded by the pipeline extractor as a function of wavelength, will yield unbiased spectra and matching orders. If your source is extracted in such a way that it does not lose the same flux fraction, it will be biased, as the spectrum in Fig. 2 is.

3.2 The Solution: Extended-Source Optimized Flats & `FLUXCON`

Luckily, this problem is easily avoided. There are two possible methods to avoid the form of extraction-driven aperture loss.

1. Form an **aperture loss correction function** (ALCF) which removes the effect. There are two methods to obtain an ALCF, which should yield independent measures. By extracting a star using the pipeline extractor with the default, expanding aperture, and then widening that aperture such that *no* flux is lost: the ratio of these two extractions is the ALCF. It's also

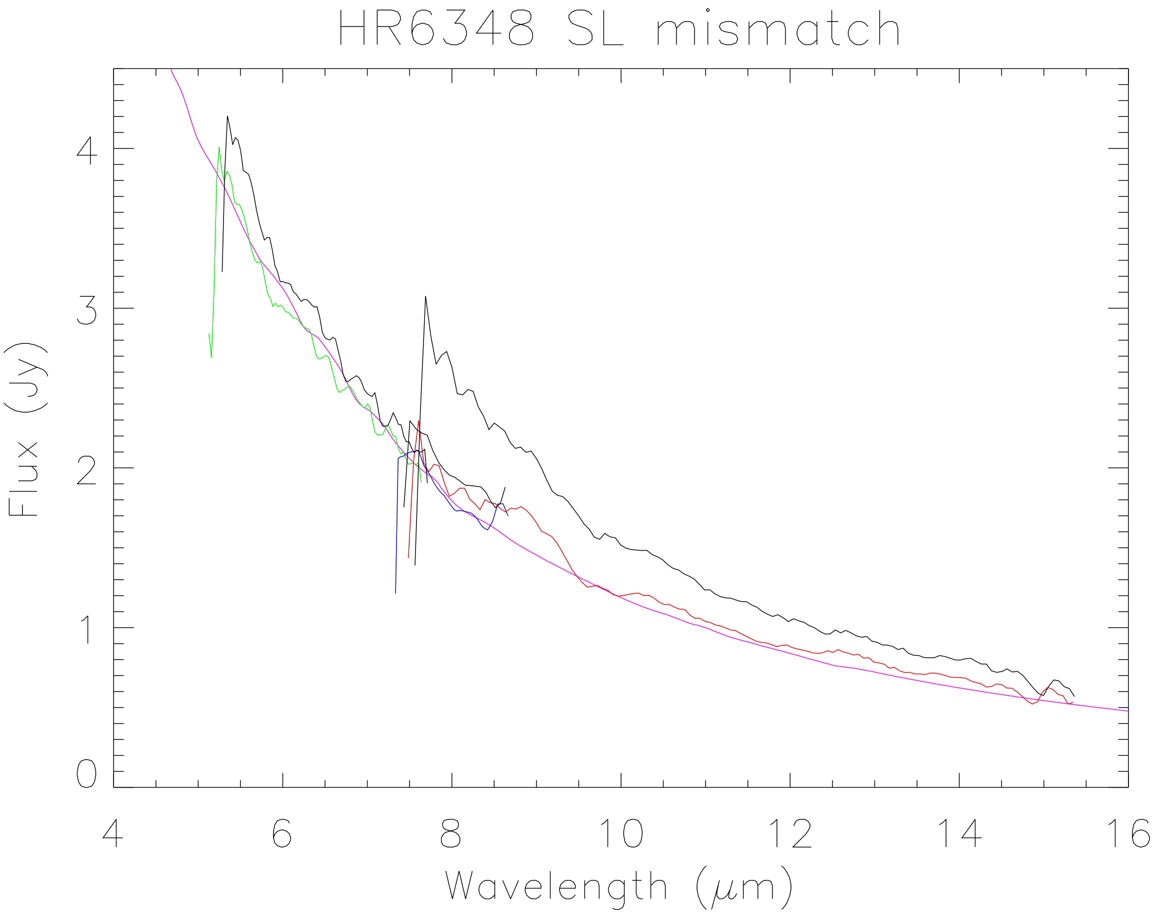

Figure 2: A “straight-sided” extraction of calibration standard star HR6348 reveals a mis-match between overlapping orders. Since the aperture size is discontinuous between orders, jumping at 7.5um from 4.25 pixels to 2.16 pixels, precisely this differential amount of flux must be discarded to recover an unbiased spectrum. Note that this is independent of the use of the IRS `FLUXCON` tables, but is implicit in the flat-fielded data themselves. The magenta curve is the model flux, and the green and red spectra from from the pipeline extractor: not surprisingly, they match the model well.

possible to extract a given star with a conservative, large extraction aperture, and divide it into the model spectrum. This method is illustrated in Fig. 3

2. A better method which doesn't require additional products and correction functions addresses the root of the problem. If calibration spectra are extracted, for the calibration pipeline only, using over-sized, bias-free straight-sided apertures, a separate set of flat fields (if necessary) and `FLUXCON` tables can be constructed which are applicable to extended sources: the ALCF will be implicitly built into them. This set could be provided alongside the standard, point-source calibration products, and used successfully

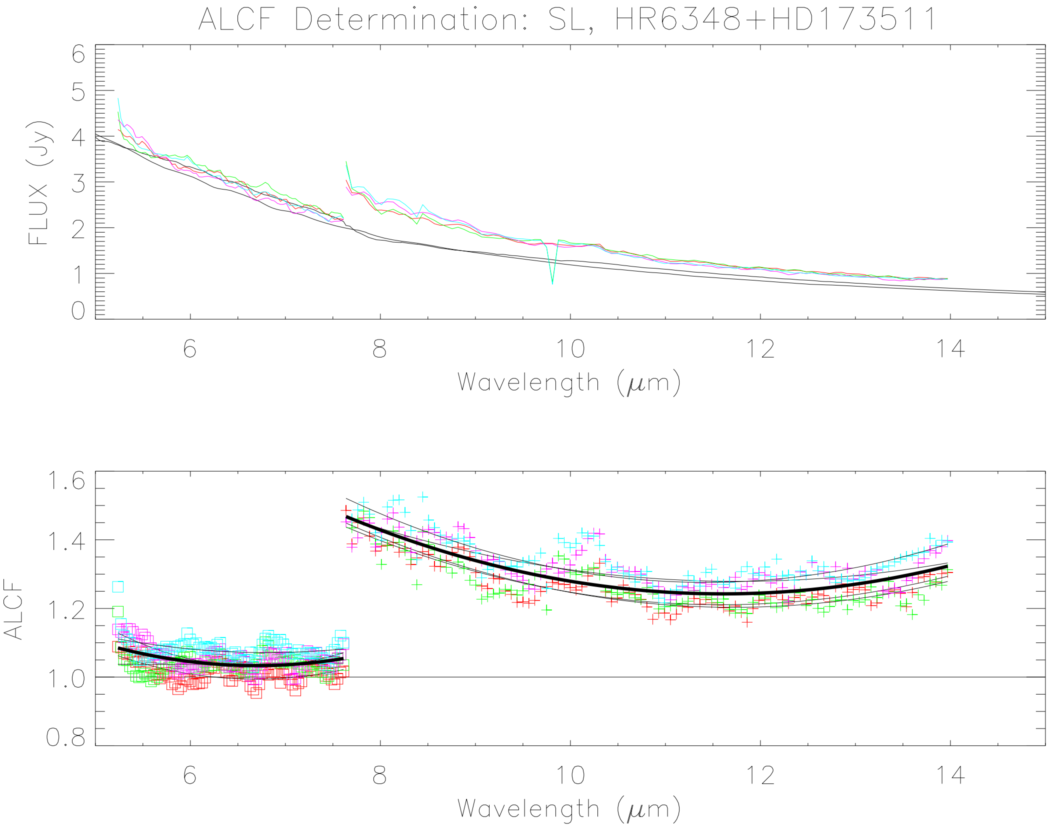

Figure 3: A single determination of ALCF by the second method: two stars are extracted with very large apertures to avoid bias, are converted to fluxes using `FLUXCON` and ratioed against their model spectra. The resulting offset between orders (a factor of ∼1.4), which results from the factor of 2 mismatch in extraction widths, is evident. A polynomial fit to the ALCF for each order is shown.

4 Diffraction Losses

4.1 The Problem: Narrow Slits, Fat Photons

Diffractive losses which vary with wavelength are a well-known problem of slit spectroscopy, especially evident when a spectrograph spans many octaves of wavelength, as does the IRS. This unavoidable loss of flux through the slit is directly related to the changing size of the telescope+instrument delivered PSF as a function of wavelength. For a point source, assumed to be precisely centered on the slit, the slit-loss is implicitly accounted for in the pipeline, and removed, to obtain the true stellar flux of calibration standards, forced to match their model spectra. I.e. diffractive losses are implicitly *taken out* by the pipeline, under the implicit assumption that the relative loss as a function of wavelength is the same from source to source and extraction to extraction. And indeed, for well-centered point sources, this will be true: they will have the same wavelength dependence of slit-loss, and the standard pipeline will recover an unbiased flux estimate for them, matching the models.

Extended sources, by definition, cannot be well-centered. Arbitrary extended sources suffer both diffraction *losses* from within the acceptance beam of the slit, and diffraction *gains* from emission which, in the absence of diffraction, would have fallen outside the beam. The net result is that spectra extracted from uniform extended sources are biased high by the pipeline, which is incorrectly assuming a constant fraction of their flux has been lost.

4.2 The Solution: PSF and Slit Modeling

Unlike the extraction losses outlined in the last section, there is no simple fix for diffraction losses, and any corrections applied may need to be guided by science choices. This is because, for extended sources, the physical area being sampled changes as a function of wavelength. For a spatially uniform extended source, the losses and gains exactly cancel each other out, such that, to recover an unbiased flux estimate, you must multiply by a **slit loss correction function** (SLCF) which is simply the fraction of the PSF which the slit admits, as a function of wavelength (see, e.g., the ISO Handbook[2], § 5.9.3).

In general, spectra of extended sources with strong and variable structure will suffer a net gain or loss, depending on the exact distribution of that structure. For instance, a slit placed adjacent to a bright ring will deliver a redder than normal spectrum, as long wavelength light from the ring diffracts *into* the slit. With full spectral maps of a region, this problem can be mitigated by convolving the image formed at each wavelength to a common reference resolution, thus using knowledge of what is "outside" the extraction aperture. A similar correction can be made using auxiliary imaging in wavelengths which overlap the image, and an assumed form of the spectrum.

Creating the uniform source SLCF requires a reasonable model of the PSF convolved against the slit acceptance beam in the slit (which can be approximated by a rectangle). This basic, ideal case, model can then be fine-tuned for individual extended sources using other knowledge of their structure. An example, roughly computed SLCF from G. Sloan's simple models (priv. communication) is in Fig. 4.

It is also possible to use the zodiacal emission as a stand-in for a uniform extended source of known (modeled) flux intensity. Extracting the zody and a point source calibrator star, correcting for the ALCF, and dividing the two will yield an estimate of the SLCF which should look roughly like Fig. 4, and can test to some degree the model PSF used.

References

2003. *The ISO Handbook*, sai-99-077/dc, version 2.1 edn.

Lloyd, C., **2003**. *The ISO LWS Beam Profile*. In *ESA SP-481: The Calibration Legacy of the ISO Mission*, 399–+

Salama, A., **2000**. *ISO Beam Profiles and Extended Source Flux Calibration*. In *ESA SP-455: ISO Beyond Point Sources: Studies of Extended Infrared Emission*, 7–+

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[2] `http://www.iso.vilspa.esa.es/manuals/HANDBOOK/lws_hb/lws_hb.pdf`

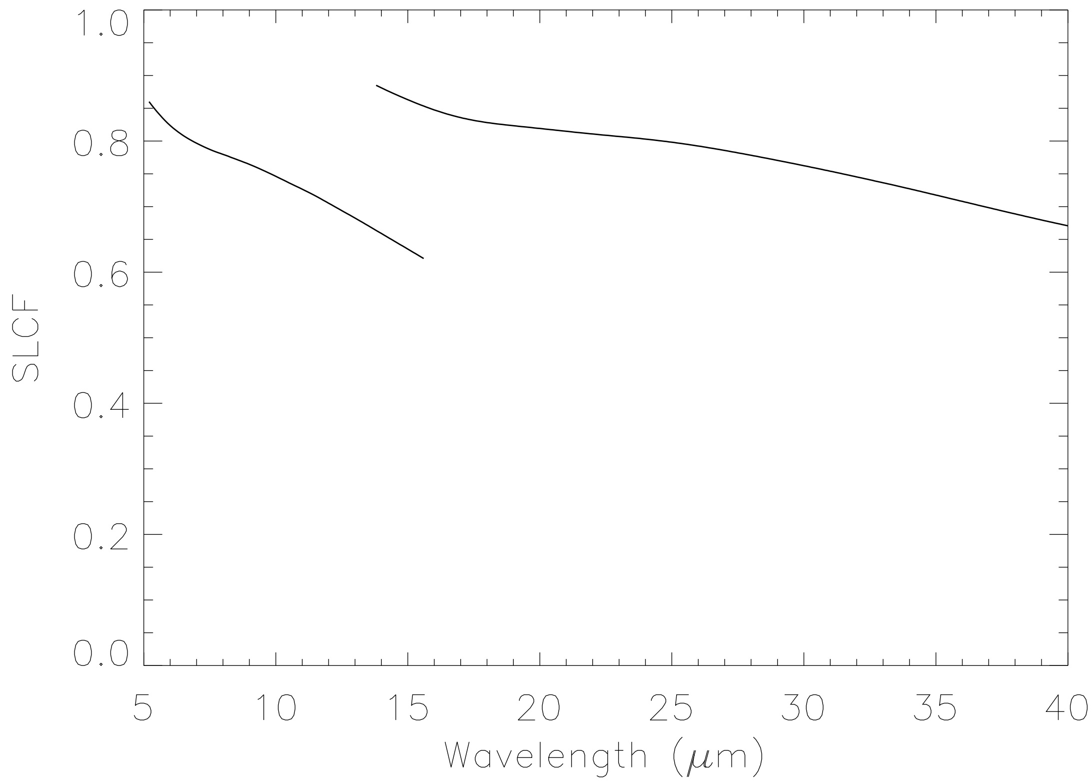

Figure 4: The *slit loss correction function* (SLCF) as a function of wavelength for IRS Short-Low and Long-Low modules. The PSF used here is only a rough approximation of the Spitzer+IRS PSF.