Camera 3 Intrapixel Sensitivity

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August 1999

ABSTRACT

The NICMOS detectors have significant sensitivity variation across individual pixels, and particularly at the pixel edges. This variation is different for each pixel. While this variation causes an overall loss of sensitivity in cameras that oversample the point-spread function (PSF), it can result in significant photometric errors when the PSF is undersampled, as is the case with NIC3. In this ISR we define the problem (up to 30% flux variation among individual images of a point source) and suggest solutions to correct the photometry of point sources in images taken through the F110W (J) and F160W (H) filters. A method of correcting the photometry based on the ratio of the flux in the peak pixel to the flux in the whole PSF is explained in detail. This method avoids the centroiding problems inherent in other correction methods, and gives a slightly smaller spread in the resulting photometry-- 2σ=0.06 mag at J, and 0.07 mag at H, during the NIC3 campaigns. This correction is to the average value detected among the test population, to conform to observations of extended targets. We also review how to correct GRISM spectra for light lost as the spectrum moves from row to row. Although these procedures work well with individual images, we strongly recommend at least three dither positions of each field or object, with at least ten pixels of motion between positions.

1. Introduction

There is a variation in sensitivity across individual pixels in any detector. While this variation does not affect photometry for over- or critically-sampled point-spread functions (PSF), if the PSF imaged onto the detector is narrower than the pixels, the total flux detected will vary depending on where the PSF is with respect to the pixel center. This situation is shown schematically in Figure 1. If the PSF is centered on the pixel corner, then most of the flux lands on the region of reduced sensitivity and the total flux received for the whole PSF can be significantly reduced compared to that received when the PSF is centered on the pixel. Thus the measured brightness of a star can vary considerably in consecutive images made with a small motion ("dither") between them.

This effect is not apparent when the PSF core is much broader than the pixel (when the PSF is well sampled by the pixel grid). This is the case for images taken in NICMOS camera 1 (NIC1) and for the longer wavelengths in camera 2 (NIC2). Camera 3 (NIC3) has pixels that subtend 0.2 arcsec on the sky and therefore, when in focus, undersamples the PSF at all wavelengths (the full width at half maximum of an in-focus monochromatic PSF at 2.2 μm wavelength is 0.21 arcsec). Thus observations of the same star at different positions on the detector (dithered observations) will yield substantially different total fluxes at the different images. Sections 2 and 3 of this report describe how to compensate, at least partially, for this loss.
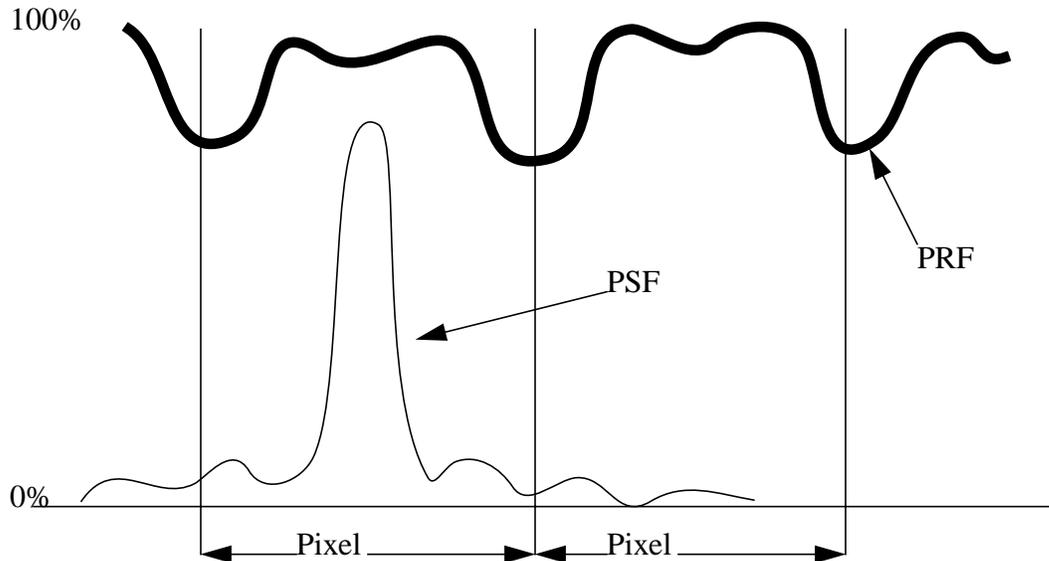
Figure 1: Schematic of the NICMOS pixel response function (PRF) (bold line) and a generic point spread function (PSF). Note that the PRF does not drop to 0 at the pixel boundaries (cf. discussion in Fruchter et al. 1999). About half of the light is in the core of the PSF, which for NIC3 is much smaller than the size of a pixel.

Figure 2 shows the variation of the FWHM of the core of the PSF against the variation in brightness for two stars in the HDF-South (out of campaign observations). The PSF gets narrower as the image gets brighter, which is expected if the flux variation is due to the presence of dead space between pixels. When the PSF is centered on a pixel, most of the light goes into that pixel and the measure PSF is fairly narrow (about 1 pixel). When the PSF is observed toward the edge or the corner of a pixel, most of the light is spread over several adjacent pixels and the measured FWHM will be much larger (e.g., 2 pixels). If most of the flux variation is caused by light lost between the pixels (as opposed to the central dip in sensitivity illustrated in Fig. 1, which occurs when the diode comes too close to the CdTe layer in the detector) a direct correlation between FWHM and amount of light

lost is expected. This is seen in Figure 2: the brighter the stellar image, the smaller its FWHM.
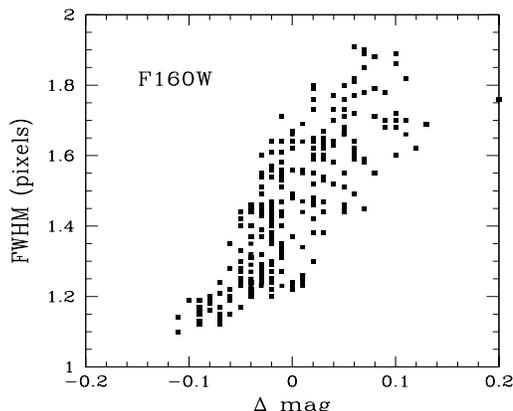
Figure 2: FWHM of the core of stellar PSFs from the HDF-S. The core gets narrower as the star appears brighter.

In addition to the imaging filters, NICMOS has three GRISMs for slitless spectroscopy. These disperse the light across NIC3, with the exact position of the spectra on the chip depending on the target position in the field of view. The dispersion direction is not precisely aligned with the detector x-axis (note: the standard "POS TARG" coordinate system is used throughout, as compared to the "detector" coordinate system, used during instrument testing and checkout). As a result the dispersed light "skips" from row to row, with much of the light being lost to the intrapixel region during each "skip". If the spectrum is bright enough to determine the position of the first skip, however, it is possible to correct for the 20% or so loss of light in the skip region. This correction is described in section 4 along with an implementation in NICMOSlook to perform this correction on spectra.

All correction software and calibration files should be available from the appropriate sites on the STScI NICMOS web site, which is under "Instruments" on the STScI site (http://www.stsci.edu) or you can email "help@stsci.edu" for more information.

2. Correction based on position

One obvious way to correct for flux variation due to intrapixel sensitivity variation is to measure the brightness of a standard star and plot how this changes with position with respect to the center of the pixel. Fruchter, Hook, and Stiavelli (1999) have analyzed stellar images in the HDF-South NICMOS Camera 3 images in both the F110W and F160W filters. A simple linear fit to the measured magnitudes as a function of radial distance from the centers of the pixels reveals a clear trend with a center-to-corner difference of 0.25 magnitude (F160W) and 0.23 magnitude (F110W). The RMS of the fit is 0.04 mag and 0.06 mag (one sigma) respectively for the two cases. The dispersion of the F110W fit is significantly reduced (to 0.045 mag), and the amplitude of the effect somewhat greater, if

the radial distance is measured from a point offset from the center of the pixel. For more details of the data and analysis please refer to Fruchter et al. (1999) and to Stiavelli et al. (1999).

Lauer (1999) has investigated intrapixel sensitivity variations on photometry for the WFPC2 as well as NICMOS. His technique involves the construction of a sub-sampled PSF based on many observations of the same area, taken with slight offsets. This PSF can then be used to map the photometric variation of an average pixel. The results of this mapping can be found in Figures 7 and 8 of Lauer (1999).

These correction procedures involve finding the position of the PSF to within a tenth of a pixel accuracy. Finding the position may entail some iteration (see discussion in Lauer 1999). Once the position is known, the value in the map at the corresponding position to the nearest pixel center to the PSF can be used to correct the flux measurement.

It is interesting that Lauer's maximum correction (30%) is considerably higher than that seen by any other investigator, even when using the same data. There are also marked asymmetries in Lauer's correction surfaces, especially at J. These may be due to the subset of the data used in determining the correction-- the details of the PSF vary over the field of view, and the FOV is not evenly sampled in the HSF-S. The four stars in the field of view all avoid the lower left quadrant of the chip. Since sensitivity increases with temperature and the chips are warmest in the corners, one expects the sensitivity map to be weighted toward PSFs that reflect the intrinsic PSF seen toward the top and the right of the NIC3 FOV. Suchkov and Galas (1999) report that the strongest aberrations are y coma and x astigmatism in NIC3. These have the effect of producing a PSF that is asymmetric toward the top of the chip, and which gets more asymmetric as you move farther from the optical axis (higher Y values). Thus an offset of the sensitivity function towards the top of the pixel would be expected, especially given the dataset used. Alternatively, this asymmetry may be due to a slight systematic mismatch during detector manufacture. Such an asymmetry would be more noticeable at shorter wavelengths because (as pointed out by Stiavelli et al. 1999) the photoelectrons generated by bluer photons have to travel farther through the detector material to the collection point than those generated by redder photons. Thus they are more affected by asymmetries in the detector.

Note that (as discussed in Lauer 1999) determining the pixel position can be influenced by the intrapixel sensitivity. This is illustrated by Figure 3, which shows some of the results from calibration program 7816 (PI Luis Colina). This program stepped a bright star across a couple of pixels in NIC3, in 0.2 pixel steps. A simple flux-weighted centroiding algorithm determined the resulting observed position, and Figure 3 shows the position perpendicular to the offset direction plotted against the position along the offset direction. The centroid gets "sucked" toward the middle of the pixel as the PSF passes it, and "snaps" away from the center as the PSF moves from one pixel to the next. Since the scan didn't run right along the middle of the pixels, the Y value of the centroid varies as well. In

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this example, the motion is a bit more than 0.05 pixel in the Y direction, while the anomalous motion in the X (scan) direction can be a factor of two off of the actual motion (0.2 pixel per step). This anomalous motion is an additional source of error (and may explain the dearth of PSFs in the corners of the pixels, as reported by Lauer 1999).
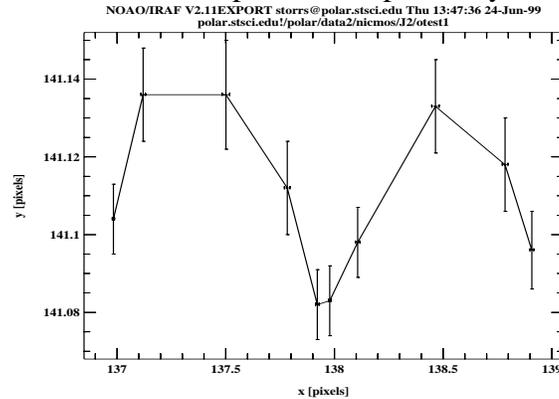
Figure 3: Position determined for observations at sub-pixel steps, scanning by 0.2 pixel steps in the X direction. The intrapixel sensitivity variation causes the measured position for the PSF to vary, as the PSF is moved across the pixel boundary.

Thus while most photometry programs give the positions of the stars to fairly high precision, the accuracy of these positions, and hence this correction for intrapixel sensitivity, can be problematical. The next section describes a correction routine that depends only on easily measurable photometric parameters of the PSF.

3. Correction based on sharpness

For an undersampled NIC3 PSF, up to half of the flux is in the peak pixel. The amount of the flux in the peak pixel depends on where the PSF is within the pixel: if its toward the center, the peak pixel will be at a maximum, while if the PSF is toward the corner the flux in the peak pixel will be at a minimum. This would be true even if there were no intrapixel sensitivity variation-- you can easily convince yourself that the flux in the peak pixel in the latter case will be about a quarter of that in the former case. If there **are** intrapixel sensitivity variations, they will have the most effect when the PSF is towards the corner of the pixel and the minimum effect when the PSF is near the center. Thus the ratio of the flux in the peak pixel to the total flux measured in the PSF measures the position of the PSF in the pixel, and hence the amount of light lost to the intrapixel sensitivity. Note that this assumes the pixels are symmetrical.

Figure 4 shows the results of program 7816 (described in section 2), when a bright point source is imaged while the spacecraft is scanned so as to move the PSF across a couple of pixels. The normalized flux in each stellar image in each scan (two in X, and two in Y) is plotted against the "sharpness ratio", the ratio of the flux in the peak pixel to that of the entire PSF. This is shown for both J (1.1 μm) and H (1.6 μm). Note that each scan is

not along the line connecting the centers of the pixels. Thus the absolute maximum and minimum ratios are not necessarily obtained. The fits to these data points are given in Table 1.
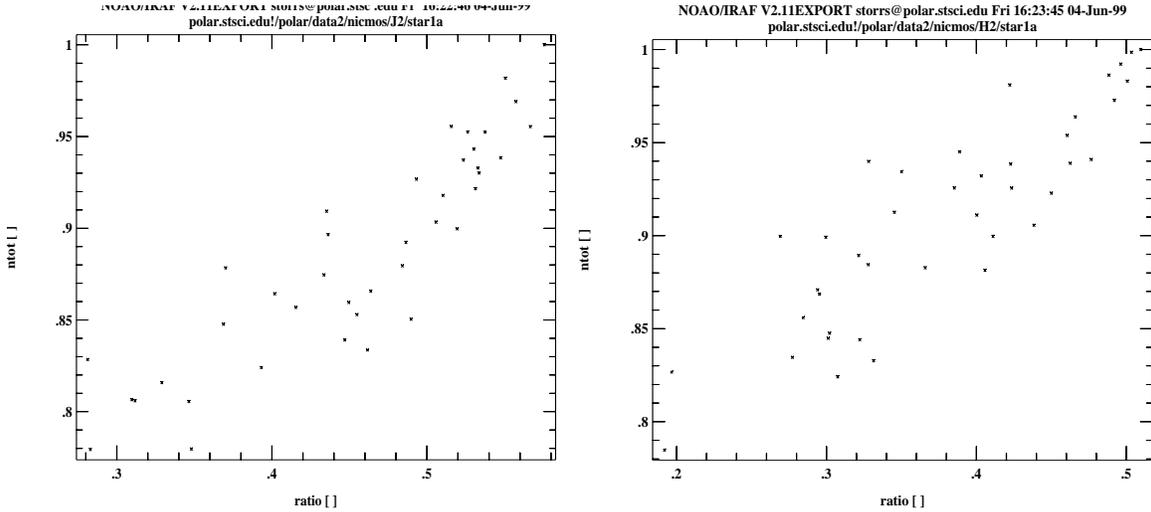
Figure 4: J(1.1 μm) and H (1.6 μm) observations in campaign mode. Forty J and H observations of standard star P330E are used to plot the normalized total flux against the "sharpness ratio". The 2σ width of the population corresponds to 0.06 mag for J, and 0.07 mag for H. The wavelength dependence of the magnitude of the effect and the dispersion agrees well with that of Fruchter et al. (1999).
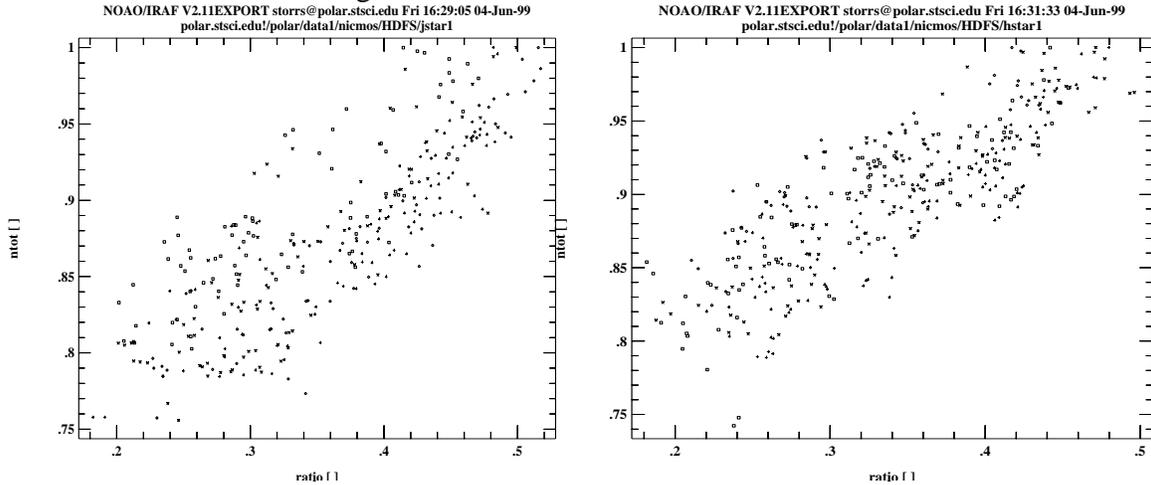
In Campaign Parameters:

Filter:	Slope:	Intercept:	Median Ratio:
J (1.1μm)	0.6108	0.6030	0.4740
H (1.6μm)	0.5577	0.6985	0.3870

Table 1. Linear fit to Figure 4. Normalized flux = slope x "brightness ratio" + intercept. To correct a star with an observed total flux and ratio to the median value, multiply the total flux by (slope*median ratio + intercept)/(slope*ratio + intercept).

Because we can't be sure we've observed the maximum brightness for a star in this limited dataset, the fit to the intercept and the median ratio value have been adjusted to the maximum ratio observed in the analysis of in-campaign PSFs in Storrs (1998). The difference from the canonical fit to the above data is within the noise. The much larger dataset for the out-of campaign fit (below) obviates the need for this small correction. In each dataset, the flux is normalized to the maximum observed for each object, to eliminate the intrinsic brightness differences among the stars observed out of campaign.

Figure 5 shows the results of a similar analysis outside of the NIC3 campaigns. Observations of four point sources in the HDF-south observations are presented, and the results of linear fits to the data are given in Table 2.

Figure 5: J (1.1 μm) and H (1.6 μm) observations out of campaign mode. 319 (J) and 368 (H) observations of four stars in the HDF-South field are used to plot the normalized total flux against the "sharpness ratio". The 2σ width of the population corresponds to 0.10 mag for J, and 0.09 mag for H.

Out of Campaign Parameters:

Filter:	Slope:	Intercept:	Median Ratio:
J (1.1μm)	0.5809	0.6678	0.3525
H (1.6μm)	0.5679	0.7060	0.3400

Table 2. Linear fit to Figure 5. Normalized flux = slope x "brightness ratio" + intercept. To correct a star with an observed total flux and ratio to the median value, multiply the total flux by (slope*median ratio + intercept)/(slope*ratio + intercept).

The width of the ±1σ envelope to the fits to Figures 4 and 5 is only slightly smaller than that for similar plots for other correction mechanisms that are based on centroiding the PSF. Even outside the campaigns, the spread around the fit is less than 0.1 mag, while the spread in the fit between total flux and distance from the center of the pixel is up to 0.12 mag. If you can determine the "sharpness ratio" (an IRAF script to do this is given in Appendix A) you can determine the actual brightness of the point source much more precisely by using this correction scheme-- the errors inherent in determination of the PSF position are sidestepped.

It is surprising that the width of the population outside the NIC3 focus campaigns is larger than that measured during the campaigns. The out of campaign measurements are for four different stars, however, and the assumption in the normalization of these stars will lead to a broader (and more realistic) spread in the population.

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Note that the "sharpness ratio" is similar to the sharpness parameter used by Hasan (1994) in determining the best focus from WFPC2 images. Hasan's sharpness parameter summed the square of each pixel in a 9x9 box centered on the PSF, and normalized this by dividing by the square of the sum of the pixels in the box. This allows for better treatment of faint stars (where sky correction might make some pixels negative) but will wash out the difference between dithered images of bright sources. Thus in general we recommend use of the "sharpness ratio" as defined in this section, for correcting NIC3 photometry.

Correction procedure:

This procedure will correct the measurement of a PSF to the median value of a large family of measurements, so that the corrected photometry of an undersampled source would equal the direct photometry of the source if it were critically sampled or extended. Reduce each image of a dithered set individually-- the results can be combined after correction, to further reduce the variation.

1. Determine the total flux in all point sources in each image, along with the peak counts in each PSF.

2. Divide the number of peak counts in each point source by the total flux in that source to determine the "sharpness ratio", R.

3. Determine the corrected total flux by multiplying the observed total flux by:

$$\frac{m\overline{R} + b}{mR + b}$$

where m is the slope and b the intercept and $\overline{R}$ the median ratio given in Tables 1 and 2, for in- and out-of-campaign observations respectively.

4. Combine the corrected individual observations of the same star as you would normally.

4. Correction of GRISM spectra

Freudling (1999) describes how slitless GRISM spectra may be corrected using NIC-MOSlook. Versions later than 6.5.3 have the correction built into them. The user is encouraged to read this paper, along with the revised version of the manual (v3.0 or higher). The basic steps are:

1. Reduce the spectra without correction to see what you've got.

2. Check the X offset on the resulting spectra: display it in `DN`, hit `Plot Response`, and use the `Xobj+` and `Xobj-` buttons to shift the curves to fit.

3. Edit the setup parameter `CORRECTPRF` to be 1.

4. Measure the spectral orientation with the `trace` option.

5. Once a good fit is obtained, use the `Use & Save Fit` option.

6. Check the fit using `Mark Objects→Pixel Boundary Crossing`.

7. Edit the GRISM parameters to select the proper prf file: amplitudes from 0.01 to 0.1 are available.

8. Extract the spectrum as usual, and compare the results to step 1. to see if it looks good.

Note that there is room for a large amount of iteration in this process. Thus efforts by different individuals may produce different results. Please check out the paper and the updated handbook for details. Figure 6 shows before and after corrections of G141 spectra of the solar-type standard, P330E.
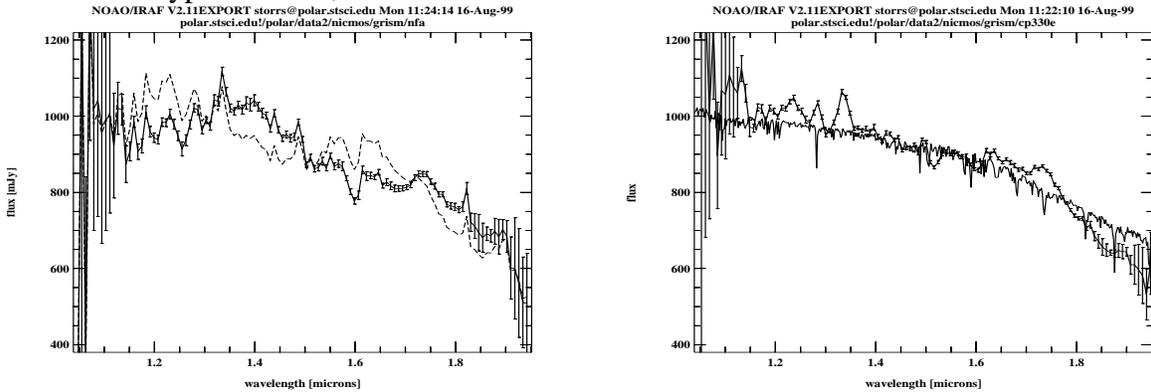
Figure 6: Left: GRISM spectra before (solid) and after (dashed) correction for PRF variation with NICMOSlook. Right: Four dithered observations, reduced separately and averaged together, compared to the actual spectrum (which is at much higher resolution).

There is a button in NICMOSlook for fitting the sharpness parameter. Experience has shown that this is most useful for high signal-to-noise spectra, however, and we recommend the above procedure for most spectra.

5. Conclusion

For photometry of individual point sources in NIC3 images, two methods of (partially) compensating for the loss of light between pixels are available. The methods described in section 2 assumes you have very good information on the actual location of the center of your PSF with respect to the pixel grid. The sensitivity maps described in this section (from Lauer 1999) allow you to correct the observed flux to what it should be, for an average PSF. An equivalent method is also presented in Stiavelli et al. (1999). Section 3 describes a correction method based on the ratio of the flux in the peak pixel in the point source image, to the flux in the whole source (the "sharpness ratio"). The total flux can be corrected by using only this ratio, without fitting the position or width of the observed PSF. Both methods work better with brighter objects than with fainter ones, due to the

intrinsically better determination of the flux in the PSF for bright targets. Please read the relevant sections and referenced papers for details and warnings.

Grism spectra can be corrected for light lost when the spectrum moves from row to row as described in section 4. This correction is much better than that for non-dispersed images as the spectra sample many pixels and so the variation in response among individual pixels is averaged out.

In all cases, complete correction for this effect is not possible. A bright point source imaged many times at J will give flux measurements that vary by 4-5% even after correction. Data taken outside the NIC3 focus campaigns are less susceptible to this problem thanks to the broader PSF, but still require correction. Future data should be taken at several (at least three) dither positions, each separated by at least ten (and a fraction) pixels.

6. References

Freudling, W (1999): "The Correction of NICMOS Grism Spectra for the Pixel Response Function", ECF electronic newsletter #1, http://ecf.eso.hq.org/newsletter/webnews1/

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Hasan (1994): "OTA Secondary Moves During SMOV", ISR OTA-16 (STScI)

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Stiavelli, M., Hanley, C., and Robberto, M. (1999): "WFC3 Near-IR Channel: PSF and Plate Scale Study"-- WFC3 ISR 1999-01

Storrs (1998): "Second NIC3 Campaign Results"-- NICMOS ISR 98-013

Suchkov, A., and Galas, G (1999): "NICMOS optical aberrations: coma and astigmatism"-- NICMOS ISR 99-003

7. Appendix A

The following is an IRAF script to perform photometry on a list of stars, possibly in different images. It sums the counts in two concentric squares around the peak position, using these to determine the total flux in the smaller box, minus the sky calculated from the difference between the smaller and larger boxes. For faint stars, a small box size of seven pixels, and a large box size of nine, works well. For brighter stars, larger boxes will be needed. In general, the larger box should have twice the area of the smaller.

Having run the script and created output file `out.tab`, you can calculate the ratio and corrected flux with the **tcalc** procedure:

```
tcalc out.tab ratio "(peak-sky)/total"
tcalc out.tab corrected "total*((0.58*0.35+0.67)/(0.58*ratio+0.67))"
```

where the slope of 0.58, intercept of 0.67, and median ratio of 0.35 are for the J band out of campaign, from Table 2. You can perform further manipulation to convert to or from countrate or Jy or magnitudes, as desired.

The script requires as input an ASCII file with three columns: the image name (including group), and the integral X and Y positions of the point source in this image. The program also requires a file called "cdfile2.dat" that contains the column descriptions of the output file, and a file called "zeros2.dat" that is used for initialization of the output file. These files look like:

cdfile2.dat:

```
name ch*10
total r f11.7 units
sky r f11.7 units
peak r f11.7 units
```

zeros2.dat:

```
foo 0. 0. 0.
```

inputfile.dat:

```
n4kr10biq_cal.fits[1] 122 132
n4kr10bnq_cal.fits[1] 120 132
n4kr10btq_cal.fits[1] 120 130
```

etc.

The script is called sqphot.cl. Put it, and the above files, in the working directory, and in IRAF type "task sqphot = sqphot.cl". You will then be able to run the script from the parameter editor "epar", as well as the command line.

```
procedure sqphot(inlist,insize,outsize,outtab)
# Procedure to do aperture photometry on images with stat.
# Reads the image name and star location from a list,
# determines the mean in concentric boxes around the
# star, and calculates the total counts in the inner box
# and the sky counts and writes them to table "outtab".
# Requires the output format file "cdfile2.dat" and
# initialization file "zeros2.dat".
#
file inlist {prompt="Input list name-- image,x,y"}
int insize {prompt="Size of inner box (pixels)"}
int outsize {prompt="Size of outer box (pixels)"}
file outtab {prompt="Name of output table (no trailer)"}
struct *in
begin
```

```
    char name
    int i,i2,o2,xm,xx,ym,yx,xc,yc
    real tot,a,b,as,bs,sky
    in = inlist
    #
    # Check if necessary IRAF/STSDAS packages are loaded
    #
      if (! defpac ("stsdas")) {
    print("Please load 'stsdas' package before running this task")
    bye
      }
      if (! defpac ("tables")) {
    print("Please load 'tables' package before running this task")
    bye
      }
      if (! defpac ("ttools")) {
    print("Please load 'ttools' package before running this task")
    bye
      }
    #
    # calculate dist. of each border from center,
    # in integer units
    #
    i2 = insize/2
    o2 = outsize/2
    i = 0
    tcreate(outtab,"cdfile2.dat","zeros2.dat")
    #
    # read in image names and star positions from file,
    # and process
    #
    while (fscan (in, name, xc, yc) != EOF) {
    print (name)
      i = i+1
      tdelete ("foo")
    # inner box
      xm = xc - i2
      xx = xc + i2
      ym = yc - i2
      yx = yc + i2
      imtab(name//"["//xm//":"//xx//","//ym//":"//yx//
"]","foo","data",pname="pix")
      tstat("foo","data")
```

```
      a = tstat.mean
      as = tstat.nrows
      tdelete ("foo")
   # outer box
      xm = xc - o2
      xx = xc + o2
      ym = yc - o2
      yx = yc + o2
      imtab(name//"["//xm//":"//xx//","//ym//":"//yx//
"]","foo","data",pname="pix")
      tstat("foo","data")
      b = tstat.mean
      bs = tstat.nrows
   #
   # Calculate total flux and sky from imstat parameters
   #
      sky = (bs*b - as*a)/(bs - as)
      tot = as*a - as*sky
   #
   # Write to output table
   #
      partab(name,outtab,"name",i)
      partab(real(tot),outtab,"total",i)
      partab(real(sky),outtab,"sky",i)
      partab(real(tstat.vmax),outtab,"peak",i)
   }
   in = ""
   end
```