IRAC/TM05-028

# Simfit Report 59

## Intra-pixel Variation Effect on Aperture Photometry

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Version 2

## 1. Summary

This report is a result of a suggestion by Dave Elliott that I use the tools of Simfit to examine the effect of pixel phase on aperture photometry that had been noticed in IRAC band 1. It was guided by the observation of Bill Glaccum that this effect was likely due to fall-off of the sensitivity at the edges of each pixel of the array (intra-pixel variation).

For this effort I used the IRAC Campaign Q observed images of a single star obtained for 12 dithers at each of 25 focal plane positions. The model images used are those described in Simfit Report 52. The conclusions are:

1. The photometry from the 300 images has considerable scatter but shows a clear trend decreasing linearly about 5% from 0.0 to 0.7 radial pixel phase. This trend is very similar to the trend given in Figure 7 in "Photometry using the Infrared Array Camera on the Spitzer Space Telescope", J. L. Hora, *et. al.*, 2005. The same effect is seen with the pixel phase measured either as a centroid of the observed image or as the shift required in the model PRF to create a model image matching the observed image.

2. Photometry carried out on the corresponding 300 simulated images created from the model given in Report 52 by simfit to best match the observed images shows neither the scatter nor the trend with pixel phase.

3. Adding a suitable parameterized intra-pixel fall-off to the model produces a trend in the simulated image photometry with the same slope and about 70% of the scatter as produced by the observed images. The model scatter is likely due to images with the same radial pixel phase having different x and y phases. It can also be affected by the different image size over the array. The additional scatter of the observed images is due to noise in the images.

4 For the optimum parameters, the pixel sensitivity mapped on a 5 x 5 set of sub-pixels has a value of 1.000 for the center 9 sub-pixels, 0.875 along the edge, and 0.813 at the corners. The mean sensitivity over the pixel is 0.91.

5. It is possible that these parametric results can be refined by using a finer spatial grid for the convolution of the intra-pixel function with the model Point Spread Function.

## 2. Observed and simulated images

The observed images are the 300 images from IRAC Campaign Q, 12 each for 25 focal plane positions, processed as Spitzer Science Center BCD images in IRAC pixel coordinates.

The simulated images are obtained from the GSFC IRAC PSF library "ioc_sep04_rj" (for Raleigh-Jeans stellar spectrum). The optimization of these images is described in Simfit Report 52, "25 Position Model Pixel Response Functions (PRF) - Description and Quality", September 3, 2005.

Each observed image has a corresponding simulated image with the centroid exactly matched to the centroid of the observed image, each calculated over a box of 7x7 pixels. The focus setting for the library images is chosen as an overall best mean focus as described in Simfit Report 52. The centroid matching is achieved by shifting the model PSF, interpolating for fractional sub-pixel. These shifts represent the actual shift of the image on the array, as apposed to the centroids, which, because of image under-sampling, do not exactly represent this shift. Both the centroids and the shifts are used in the analysis below.

## 3. Aperture photometry

The photometry is obtained by summing the pixel values over a square 17x17 pixel (20.8x20.8 arcsecond) aperture. It is shown in Simfit Report 54, "Effect of Pixel Phase on IRAC Channel 1 Aperture Photometry and Noise-pixels" that for the model images, a 17x17 pixel aperture captures 97.5% of the flux in a point source. Also, for the model images, the photometric result is independent of pixel phase, that is, there is negligible edge effect from pixel phase for that size aperture. Thus the variation of photometry with pixel phase for the observed images is likely to be due to intra-pixel variation.

## 4. Model intra-pixel variation

The process of obtaining an IRAC image from the model PSF with sampling at 1/5 the IRAC pixel size involves summing the PSF values over each IRAC pixel. In past analysis, I have done this giving equal weight to each PSF point in the summing. However, it is equally possible to give unequal weights with a fall of at the pixel edge. I have added this step to the Simfit analysis to attempt to reproduce with simulated images the pixel phase effect on aperture photometry encountered with observed images.

In the absence of a measured or theoretical intra-pixel response for IRAC Channel 1, I have created an empirical response function for the model images with two parameters that can be adjusted to duplicate the observed pixel phase effect. A version of this function was first presented in Simfit Report 47, "Effect of Pixel Response Fall-off on Simfit", January 5, 2005. The requirements I imposed on the response function are:

1) The function is expressed as a polynomial in pixel coordinates x,y each with a range from -0.5 to +0.5.
2) The maximum value is 1.00 at the pixel center with identical x and y fall-off to each edge. This requires that the polynomial contain only even powers in x and y.
3) The value of the response at the center of the edge of each pixel is 1 – *depth*
4) The distance from edge center to the point where the response has fallen half way to depth is the *width*
5) The first and second derivatives at the edge are zero.

The resulting function in x and y is

$$\text{response} = 1 - \text{depth} + [1 - (a_2 x^2 + a_4 x^4 + a_6 x^6)^{\text{powr(width)}}] \times [1 - (a_2 y^2 + a_4 y^4 + a_6 y^6)^{\text{powr(width)}}]$$

Where

$$\text{power(width)} = \frac{\ln(0.5)}{\ln[a_2 \cdot 0.25 \cdot (1 - \text{width})^2 + a_4 \cdot 0.25 \cdot (1 - \text{width})^4 + a_6 \cdot 0.25 \cdot (1 - \text{width})^6}$$

Figure 1 shows surface plots for the response function (intra-pixel variation) for depth of 0.25 and for widths 0.10, 0.20, and 0,30. The combination of depth = 0.25 and width 0.20 appears to create a pixel phase effect most closely matching the observed effect. However, slightly different combinations of depth and width do nearly as well.

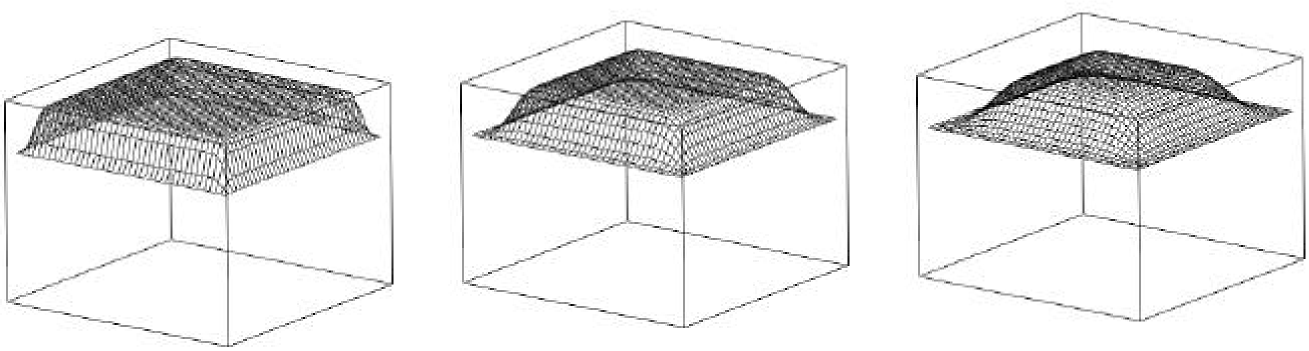


**Figure 1.** Three examples of the empirical intra-pixel response function. Each has a fall-off of response at the pixel edge of 0.25. The function at the left has a width of the fall-off of 0.1 pixel, the center 0.2, and the right 0.3. The 0.2 width fits the observed data the best.

## 5. Observed images results

Figure 2 is a plot of aperture photometry versus the centroid radius given by Joe Hora. The photometric results are normalized so that the median is 1.00. There is considerable scatter in the photometric numbers with a distinct downward trend with a slope of -0.0535.

Figure 3 gives a similar plot obtained by Simfit from IRAC Campaign Q images of a single star. The centroids, as indicated above, are calculated over a 7x7 pixel box centered on the source. The photometry is normalized to the median. The scatter of the photometry is similar and the downward trend has a slope of -0.056, nearly the same as Figure 2. Also shown in Figure 3 is a histogram of the distribution of centroid radius. The stepped line shows the distribution for uniform distribution of centroids over the pixel area. The difference between the observed and uniform distribution is likely due to the undersampling of the star image which cause the centroid to not exactly follow the telescope shifts (assuming that the telescope pointing shifts are uniform over the pixel).

Figure 4 shows the same result as Figure 3 except that the plot is versus the radius of the shift as determined by fitting the model images to each observed image. The downward trend has a smaller slope (-0.048). The histogram plot at the right shows that the observed shifts also differ from a uniform distribution but are shifted in opposite direction. Plotting versus the centroids and the shifts show the same effect. Since the centroids are simpler to calculate, they are probably a satisfactory parameter for making a pixel phase correction to the photometry.

## 6. Simulated images results

Figure 5 shows aperture photometry of the simulated images corresponding to the observed images plotted versus the centroid radius. These simulated images are calculated without any intra-pixel variation. There is no scatter and all values are the same.

Figure 6 shows aperture photometry of the simulated images with the intra-pixel variation function used in creating the simulated images. The parameters for the function described in Section 4 are depth 0.25 and width 0.2. The x-axis of the plot is radial centroid. The photometry has a similar trend as for the observed images with a slope of -0.048 compared with the slope of -0.056 for the observed images. The slope for the simulated images can be easily adjusted to the observed value by changing the depth or width parameter. The table at the right of Figure 6 shows the weighting values determined from the intra-pixel variation given in Section 4. These are applied when summing the model PSF to the IRAC pixel size. The mean weighting is 0.91 indicating that the loss of response from this effect is 9%.

Figure 7 shows the same plot with the photometry plotted versus the radial shift rather than the radial centroid. The appearance and slope are the same.

There is scatter in the simulated image plot, although it is less than that of the observed image plots.

## 7. Cause of the scatter

The scatter for the simulated images is possibly due to images with the same radial pixel phase having different x and y phases. It can also be affected by the different image size over the array. These effects should be the same for the observed and simulated data. The larger scatter in the observed data relative to the simulated data is likely due to the noise in the observations. In the Simfit program, along with analyzing the observed star images, aperture photometry was carried out on a similar 17x17 pixel square away from any star. The resulting standard deviation from the mean of this photometry on a blank part of the field is 0.0058. Adding in quadrature this value to the 0.0059 standard deviation for the simulated data gives 0.0083 which does not account for all of the standard deviation for the observed star image of 0.0139.

The possible causes of the scatter in the simulated image plots will be examined in the revised version of this report.

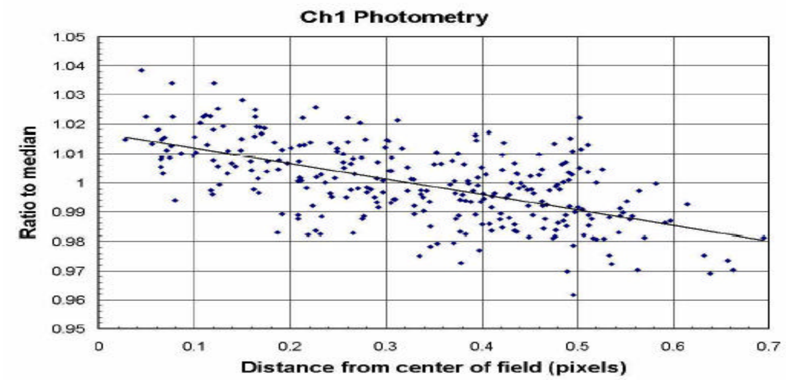



**Figure 2. Plot of IRAC Channel 1 aperture photometry versus radial pixel phase.** This plot appears in "Photometry using the Infrared Array Camera on the Spitzer Space Telescope", J. L. Hora, *et. al.*, 2005. The plotted flux is normalized by dividing by the median flux. The slope of the best fit straight line is -0.0535.

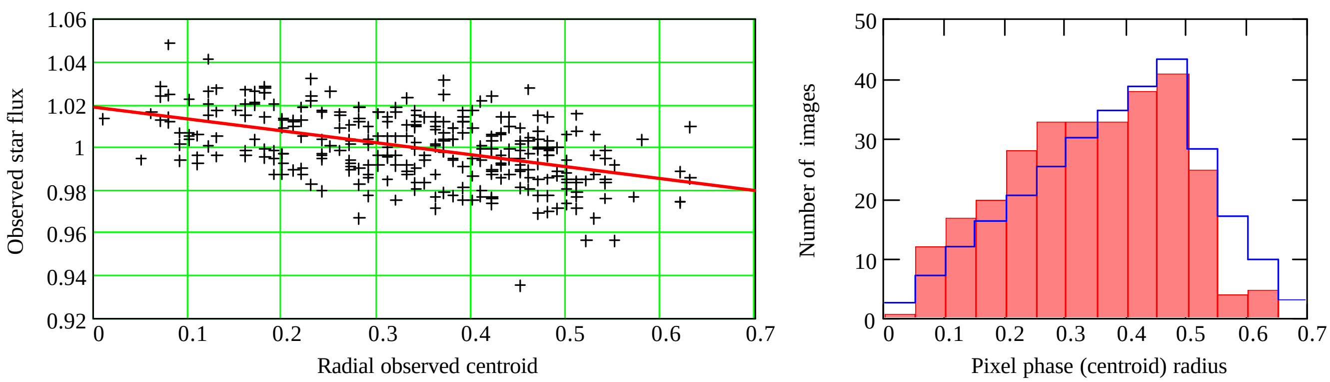



**Figure 3. Campaign Q Channel 1 observed image photometry versus radial centroid pixel phase from Simfit**. The plotted observed star flux is normalized by the median flux which is 24125. The slope of the best-fit straight line is -0.056. The standard deviation from the line is 0.014. The histogram shows the distribution with radial centroid pixel phase. The stepped line is the histogram for uniform distribution of the centroids over a pixel.

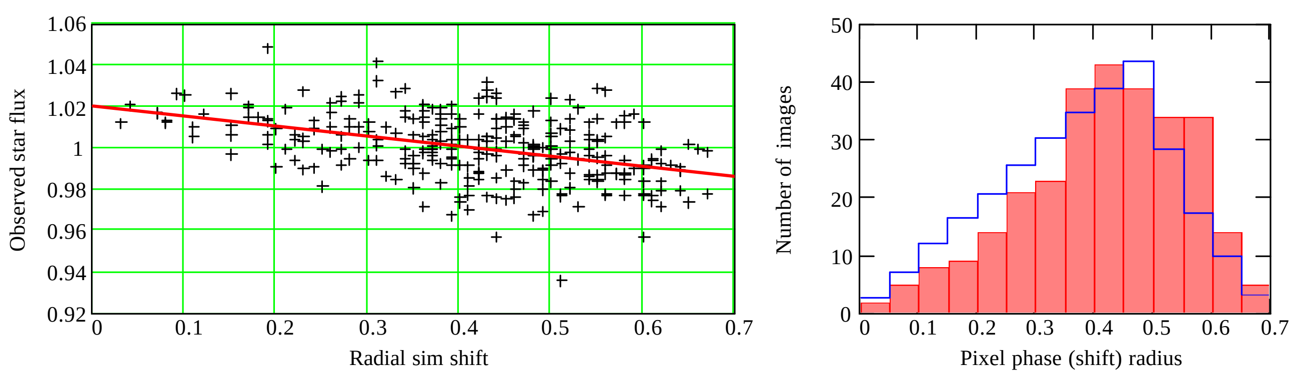



**Figure 4. The same as Figure 2 except that the flux is plotted versus the pixel shifts, rather than centroids.** The observed star flux is normalized by the median flux. The slope of the best-fit straight line is -0.048. The standard deviation from the line is 0.014. The histogram shows the distribution with radial shift pixel phase. The stepped line is the histogram for uniform distribution of the shifts over a pixel.

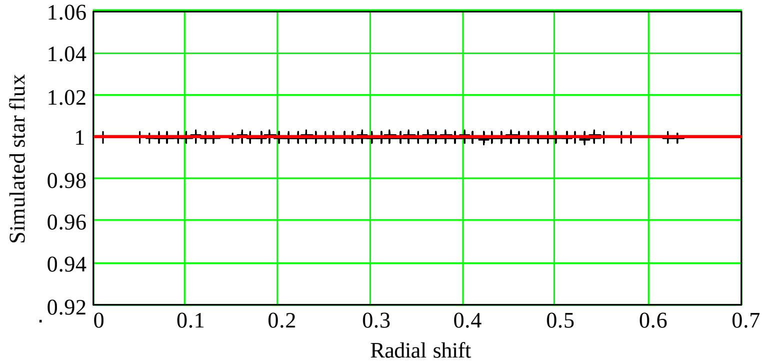
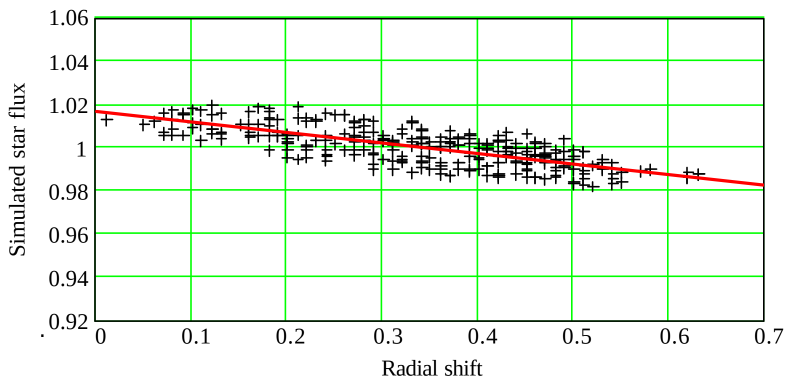



**Figure 5. Campaign Q Channel 1 simulated image photometry versus radial centroid pixel phase from Simfit.** The simulated stars are created with the focus and centroid which gives a best fit to the corresponding observed image. The simulated star flux is normalized for a median of 1.00. The slope of the best-fit straight line is 0.000. The standard deviation from the line is 0.000.




$$\text{mean}(\text{intrapix}) = 0.910$$

$$\text{intrapix} = \begin{pmatrix} 0.813 & 0.875 & 0.875 & 0.875 & 0.813 \\ 0.875 & 1 & 1 & 1 & 0.875 \\ 0.875 & 1 & 1 & 1 & 0.875 \\ 0.875 & 1 & 1 & 1 & 0.875 \\ 0.813 & 0.875 & 0.875 & 0.875 & 0.813 \end{pmatrix}$$

**Figure 6. Campaign Q Channel 1 simulated image photometry versus radial centroid pixel phase from with intra-pixel sensitivity variation.** The simulated stars are created with the focus and centroid which gives a best fit to the corresponding observed image. The conversion from model PSF with sub-pixels 1/5 the IRAC pixel size to pixel response using the weighting table at the right. The mean weight is 0.910. The smallest weight at the corner is 0.813. The simulated star flux is normalized for a median of 1.00. The slope of the best-fit straight line is -0.048. The standard deviation from the line is 0.006.

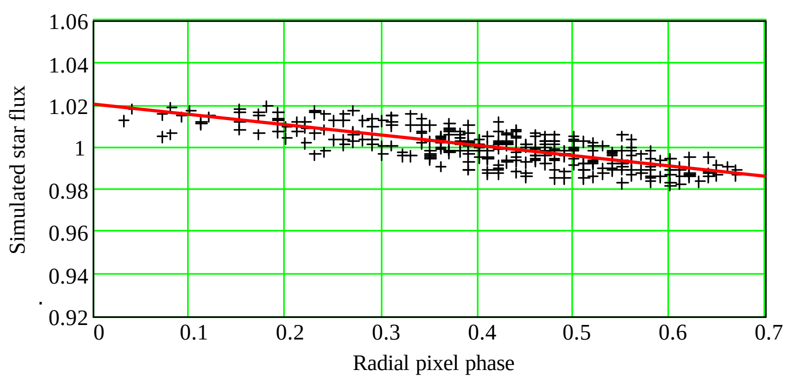



**Figure 7. The same as Figure 5 except that the flux is plotted versus the pixel shifts, rather than centroids.** The simulated star flux is normalized for a median of 1.00. The slope of the best-fit straight line is -0.049. The standard deviation from the line is 0.006.