A Comparison of GLIMPSEII and GALCEN Source Lists Based on GALCEN IRAC Observations

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1 Brief Overview

The v2.0 GLIMPSEII (Galactic longitude of -10 degrees to +10 degrees) source lists include observations of three types:

1. Areas observed only by GALCEN (SPITZER GO program, PI-Stolovy) (a small irregular patch including the Galactic center, slightly more than 1 sq. deg at the Galactic center).
2. Areas observed by GALCEN and also by GLIMPSEII (a small irregular annulus around the Galactic center).
3. Areas observed only by GLIMPSEII (most of the GLIMPSEII coverage).

In this document we compare the GALCEN (Galactic center) catalog (Ramirez et. al., 2008, ApJS, 175, 147) and the GLIMPSEII Catalog (v2.0) for sources of type-1 above. This is a comparison of two independent source extraction methods on the same IRAC data. Such a comparison is useful for improving photometric accuracy and error analysis. Section 2 gives the overview comparison between the GALCEN and GLIMPSEII magnitudes. Section 3 discusses the differences found. The results are summarized in Section 4.

2 Comparison of Fluxes and Uncertainties

GALCEN analyzed their data using the SSC software MOPEX and published a point source catalog (Ramirez et. al. 2008). GLIMPSEII analyzed both GALCEN and GLIMPSEII data together to produce its own point source Catalog. GLIMPSEII uses a modified version of DAOPHOT (see details at http://www.astro.wisc.edu/sirtf/docs.html). The following comparisons have been made in the central region (type 1 described above) from Galactic longitude of -0.43 to +0.81 degrees and Galactic latitude of -0.52 to 0.50 degrees. Since this region was covered only by GALCEN observations, the source catalogs being compared are based on exactly the same observations, with the exception that GLIMPSEII did not process any sub-array mode data observed by GALCEN. GALCEN used sub-array mode data to determine the magnitudes for their brightest sources. The GALCEN catalog contains 355,632 sources in this region while the GLIMPSEII Catalog contains 477,770. Sources were initially matched when their positions agreed to within 2.0” in Galactic longitude and latitude and there were no other confusing sources within that matching distance. This list was further pared down to only the sources that matched to within 0.7” in Galactic longitude and latitude. This ensures the sources are well matched and not badly confused by other possible nearby sources (Fig.1). This list contains 256627 matched sources. Not all matched sources have magnitudes in all 4 channels. Our analysis was performed channel by channel, therefore only when a matched source had a magnitude entry in both the GALCEN and GLIMPSEII catalogs did it get included in this analysis. This resulted in the following numbers per channel used in this comparison.

IRAC[3.6] 211,919 matched sources had magnitudes in both GALCEN and GLIMPSEII lists.
IRAC[4.5] 188,143 matched sources had magnitudes in both GALCEN and GLIMPSEII lists.
IRAC[5.8] 143,726 matched sources had magnitudes in both GALCEN and GLIMPSEII lists.
IRAC[8.0] 80,056 matched sources had magnitudes in both GALCEN and GLIMPSEII lists.

Over 92% of these matched sources had the GALCEN “2+1” flag set meaning the GALCEN data met the GLIMPSEII 2+1 Catalog criteria.

We find evidence of magnitude discrepancies between the two source lists (Fig. 2). There are three primary differences.

First, throughout the entire range of magnitudes, and in all four IRAC channels, the distribution of magnitude difference (GLIMPSEII mag. minus GALCEN mag.) is greater (2-3 times) than would be expected by combining the magnitude uncertainties from the individual source lists in quadrature.

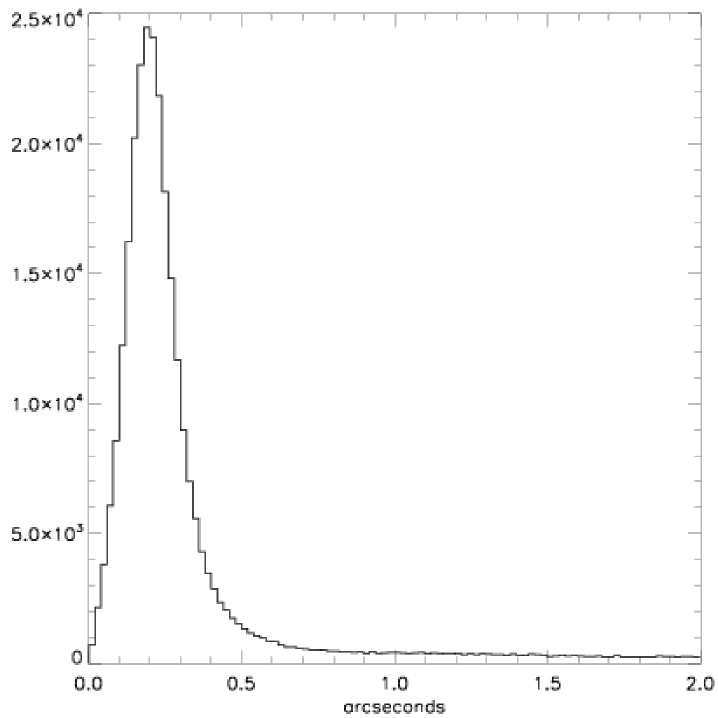

Figure 1: Histogram of the absolute separation between matched GALCEN and GLIMPSEII sources in arcseconds. The bins are 0.02 arcsecond bins. Only matches with less than a separation of 0.7 arcseconds were used in this comparison.

Second, for faint stars -- those within 2 to 3 magnitudes of the faint limit – the GALCEN magnitudes are systematically fainter than GLIMPSEII magnitudes. This is true in all four IRAC channels, though less so at IRAC[8.0] than in the other three channels. A typical offset is on the order of 0.25 magnitudes, and is worse for the faintest stars (Fig. 3).

Third, for stars within 1 to 2 magnitudes of the GLIMPSEII bright limits (magnitude limits of 7.0, 6.5, 4.0 and 4.0 for channels 1 through 4 respectively), GALCEN and GLIMPSEII magnitudes exhibit systematic offsets. Each IRAC channel has its own offset.

At IRAC[3.6], GALCEN magnitudes are brighter (roughly 0.10 mag.) than GLIMPSEII
At IRAC[4.5], GALCEN magnitudes are slightly brighter than GLIMPSEII (only the brightest stars)
At IRAC[5.8], GALCEN magnitudes are slightly fainter than GLIMPSEII
At IRAC[8.0], GALCEN magnitudes are fainter (roughly 0.2 mag.) than GLIMPSEII

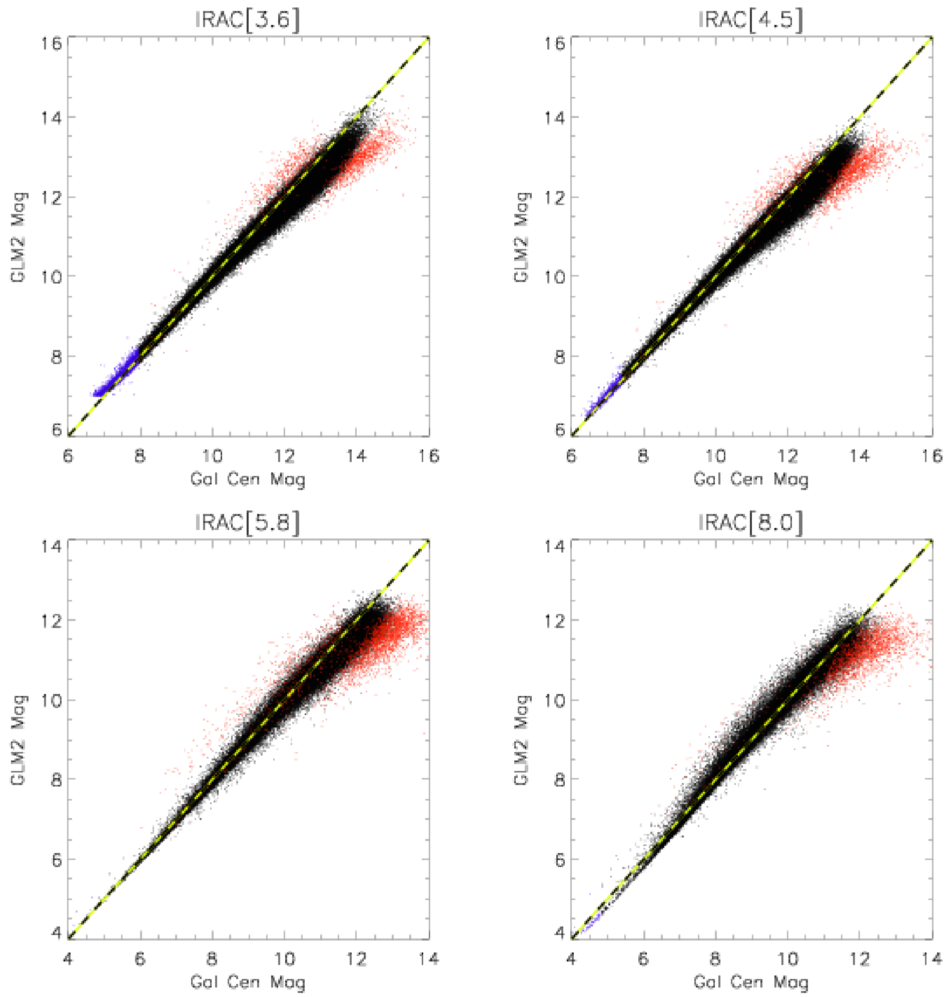

Figure 2: Comparison between GALCEN and GLIMPSEII magnitudes. Data in red are sources for which GALCEN used aperture photometry, data in blue are where GALCEN used sub-array mode data and black data points are where GALCEN used PRF fitting results. The dashed line delineates exact agreement.

3 Discussion

3.1 GLIMPSEII Uncertainty Estimates

It appears that magnitude uncertainties are being under-estimated in one or both source lists. This can be demonstrated by calculating a 'sigma factor'. The sigma factor is the difference between the GALCEN and GLIMPSEII catalog magnitudes divided by the square root of the sum of the uncertainties squared. We consider the two catalogs in statistical agreement when the histogram of the sigma factors for a matched dataset is well represented by a Gaussian curve centered at zero with a standard deviation of 1.0. We provide Figure 4 as a typical example that the uncertainties are too small for these catalogs to be in agreement. IRAC[3.6] data in the magnitude range of 9.0 to 10.0 *appears* to show good agreement between the GALCEN and GLIMPSEII magnitudes (upper left panel of Fig. 4).

For these data we calculated the sigma factors for each source and plotted that distribution in the upper right panel of Figure 4. The solid line is the best fit Gaussian for the histogram, the dashed curve is the Gaussian with a sigma value of 1.0. Since the distribution is broader than the dashed curve, this indicates that differences between the two catalog magnitudes are statistically larger than their combined uncertainties, (i.e. the quoted uncertainties are too small). The GALCEN channel 1 uncertainties are nearly always smaller than the GLIMPSEII uncertainties. The lower left panel of Figure 4 shows what happens if you increase the GALCEN uncertainties to be as large as the GLIMPSEII uncertainties; the histogram is still too broad. The lower right panel of Figure 4 shows that to bring the two catalogs into statistical agreement not only do the GALCEN uncertainties need to be increased to the GLIMPSEII values but an additional 0.01 magnitudes of uncertainty needs to be added to both catalogs. This evidence of under estimating uncertainties is found in all 4 channels and is exacerbated at fainter magnitudes where the magnitude agreement between the two catalogs diverge.

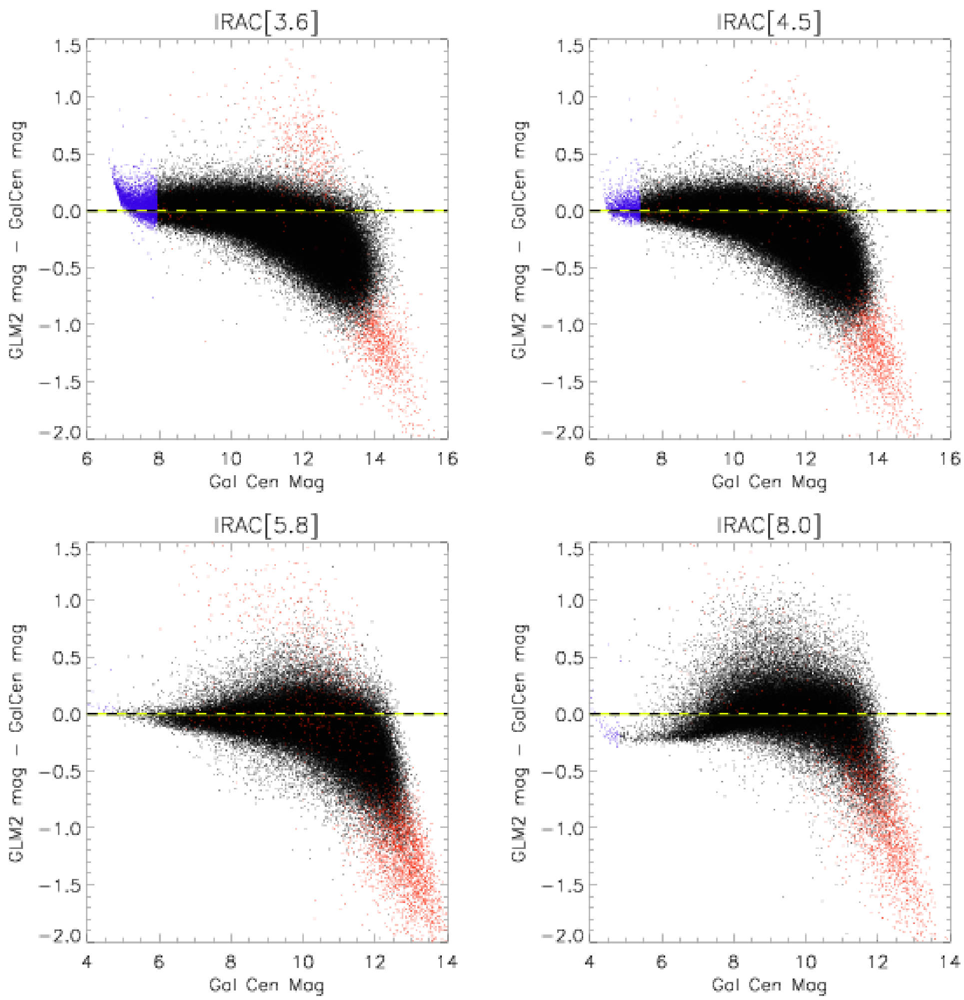

Figure 3: Magnitude difference between GALCEN and GLIMPSEII magnitudes. Colored data points are the same as in Figure 2.

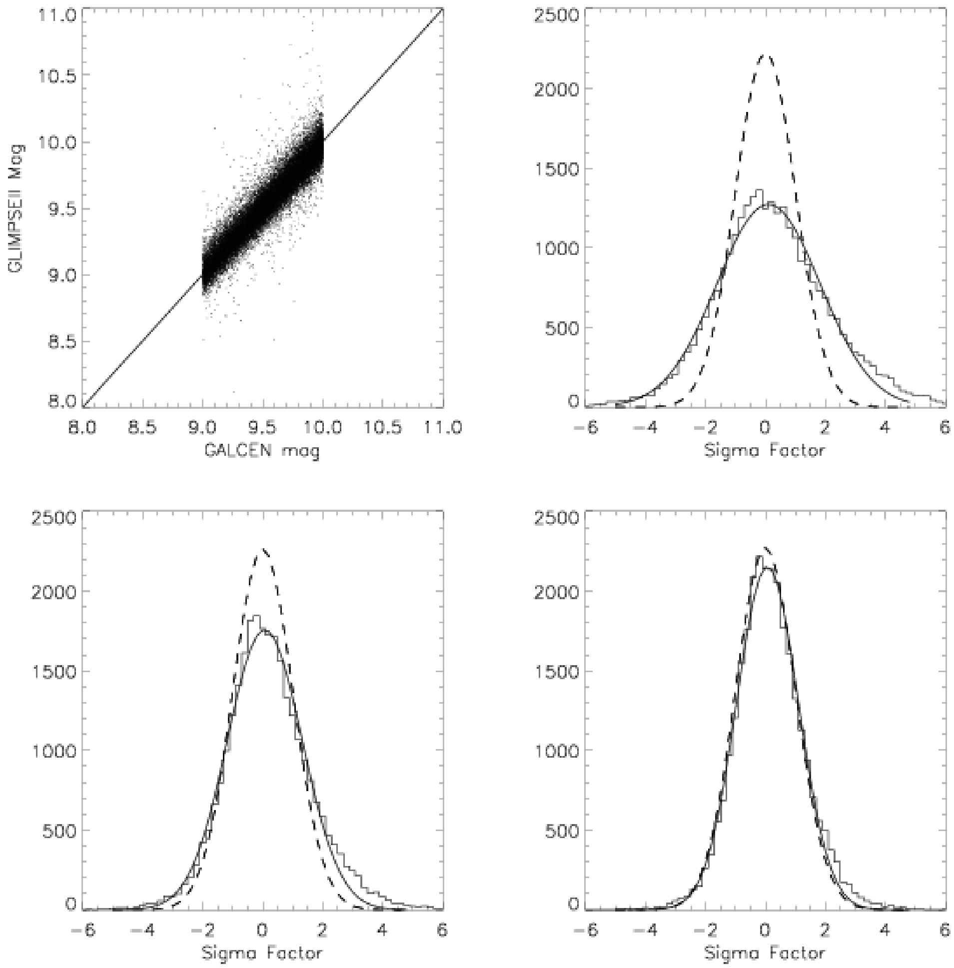

Figure 4: IRAC [3.6] data in the magnitude range of 9.0 to 10.0. Sigma Factor = (GC_mag – GLMII_mag)/sqrt(GC_unc^2 + GLMII_unc^2). Upper left panel shows correlation between GALCEN and GLIMPSEII magnitudes. Upper right panel shows the histogram of the sigma factors using the uncertainties quoted in the GALCEN and GLIMPSEII catalogs. The solid curve is the best fit Gaussian to the histogram. The dashed curve is a Gaussian centered at 0.0 with a standard deviation of 1.0; the desired distribution. Lower left panel shows the histogram for the sigma factors when you increase the GALCEN uncertainties to the GLIMPSEII values. Lower right panel shows the data when GALCEN uncertainties are increased to the GLIMPSEII uncertainties and both GALCEN and GLIMPSEII uncertainties are additionally increased by 0.01 magnitudes.

GLIMPSEII conducted an independent analysis on its quoted uncertainties. Because GLIMPSEII extracts its magnitudes from the IRAC individual frames and not from the mosaics of multiple frame data, GLIMPSEII can assess the validity of its quoted uncertainties by comparing the actual differences between repeated extractions and the quoted uncertainties for those individual extractions. Analysis of the entire GLIMPSEII region is discussed in section 3.2 of the GLIMPSEII v2.0 Data Release

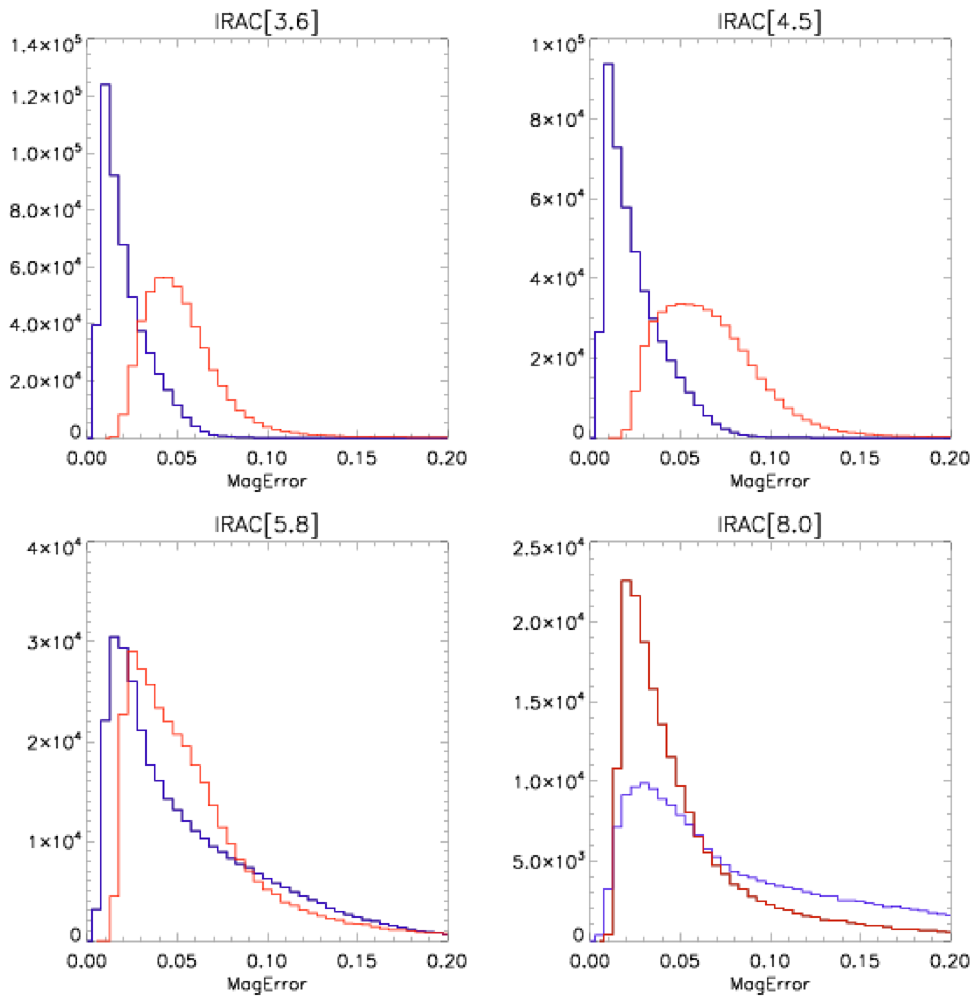

Figure 5: Histogram of the distribution of quoted magnitude uncertainties binned at 0.005 magnitudes. GALCEN data are in blue and GLIMPSEII data are in red.

Document. The results of the analysis indicate that the uncertainties in channels 1 and 3 may be slightly under-estimated, channel 2 uncertainties are roughly 10% over-estimated and channel 4 uncertainties are also under-estimated by 20% to 100% (typically 35%). Currently for the GLIMPSEII IRAC[8.0] magnitudes, the uncertainties peak around 0.025 magnitudes (see Fig 5.), thus even a 100% increase in channel 4 uncertainties would result in typical uncertainties of 0.05 magnitudes, which would put the channel 4 uncertainty histogram more in agreement with the other channels than it is presently. The cause of these discrepancies is not fully understood but may be a function of the diffuse background and crowding, as well as a minimum uncertainty level. The same analysis can be used in conjunction with known flux standards. Using the GLIMPSEII network of flux calibration sources (see section 3.2 of the GLIMPSEII v2.0 Data Release Document and section 3.5 below) a similar study of the 'sigma factors' comparing the magnitude differences between GLIMPSEII magnitudes and the predicted magnitudes for our flux calibrators likewise indicates a small degree of under-estimation of the GLIMPSEII uncertainties. From this analysis an additional amount of 0.03, 0.015, 0.03, and 0.04 magnitudes of uncertainty, for channels 1 to 4 respectively, were required to be added to the GLIMPSEII uncertainties for the flux calibrators to bring them into statistical agreement with the predicted magnitudes. These additional uncertainties qualitatively agree with the earlier analysis in the sense that channel 4 was the worst, channel 2 was the best and channels 1 and 3 were in between. However we cannot put as much reliance on this second analysis since it is based on a very limited data set, less than 100 calibration sources total. It is instructive, since it is based on an independent set of predicted magnitudes, in demonstrating that with the difficulties of source extraction in crowded fields and complex diffuse backgrounds, an additional amount of uncertainty for all quoted magnitudes may be required. For GLIMPSEII data, at maximum, an addition of a few hundredths of a magnitude of uncertainty would not seem unreasonable.

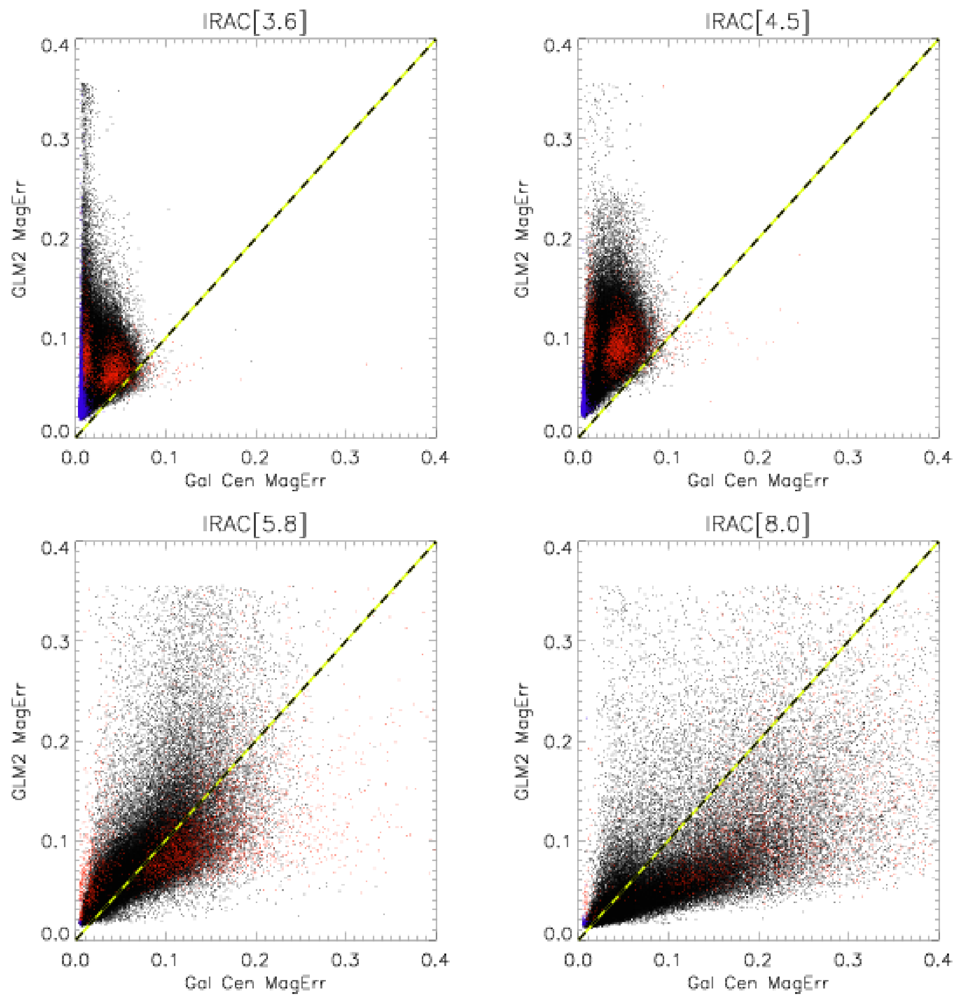

Figure 6: Comparison of GALCEN and GLIMPSEII magnitude uncertainties. Colored data points are the same as in Figs 2 and 3.

3.2 GALCEN Uncertainty Estimates

We now address the GALCEN uncertainties with respect to the GLIMPSEII uncertainties. In IRAC[3.6] and IRAC[4.5] the GALCEN uncertainties for a given source are almost always smaller than those appearing in the GLIMPSEII source list (Figs. 5 and 6). In IRAC[8.0] the GLIMPSEII uncertainties are often smaller than the GALCEN uncertainties. But even raising the uncertainties to the larger values would not bring the two source lists into statistical agreement. As discussed above the

GLIMPSEII uncertainties may require adjustment. However the adjustments are stated to be small for IRAC[3.6] and IRAC[5.8], and typically a 35% increase in IRAC[8.0], these adjustments are typically less than a 0.03 magnitude increase. Since GALCEN uncertainties are typically smaller than the GLIMPSEII uncertainties, we suspect the GALCEN uncertainties are under estimated. In our analysis we used the GALCEN magnitude uncertainty but noticed that the GALCEN signal-to-noise ratio (SNR) is an unrelated quantity. The GLIMPSEII data, as well as the associated 2MASS data, have a well determined relationship between the stated SNR and the quoted uncertainties; the SNR is simply the flux divided by the flux uncertainty. This is not the case with the GALCEN SNR where MOPEX generates a SNR based on SNR of the peak pixel of the source. It is also important to note that the GALCEN team used multiple methods in determining fluxes. They used both a PRF (point response function) fitting routine as well as an aperture photometry method. PRF fitting is the preferred method (Ramirez et. al. 2008) however PRF results were scaled by a factor determined from the aperture photometry results. Ramirez et. al. state "we found that the PRF fluxes and aperture fluxes agreed to within 12% overall." Figure 5 displays the histogram plot of the distribution of quoted uncertainties. The GALCEN uncertainties (plotted in blue), for all 4 channels, peak well below 0.05 magnitudes of uncertainty (for channel 1 and channel 2 the peak is near 0.01). GLIMPSEII data generally peak at or above 0.05 (except for IRAC[8.0] which has been stated earlier to be known to be too small). It seems unlikely that the GALCEN uncertainties can be reasonably assessed as better than 0.05 magnitudes when they state that their agreement between PRF and aperture photometry was on the order of 12% (which corresponds roughly to 0.12 magnitudes of uncertainty). We therefore conclude, that in general, the GALCEN uncertainties are likely under-estimated, and potentially greatly under-estimated. With the complexity of source extraction in crowded fields and complex diffuse backgrounds, uncertainties on the order of 0.05 to 0.08 magnitudes (5 to 8% uncertainties) do not seem unrealistic; however 0.01 magnitudes (1% uncertainties) seem unreasonably small.

Regarding the GALCEN processing, it has recently been determined that the PRFs provided by SSC for IRAC source extraction are not ideal due to the under-sampled nature of the IRAC point spread function (see: http://ssc.spitzer.caltech.edu/postbcd/mopex.html). It is also likely that the lower uncertainties in the MOPEX PRF flux estimate published in the GALCEN survey are linked to these non-ideal PRFs (Stolovy; private communication)

3.3 Faint Star Discrepancies

The faint-star discrepancies are worse in areas with high confusion (high density of closely packed faint stars). GLIMPSEII extracts more stars than does GALCEN (Figs 7 and 8), which leads to GLIMPSEII having systematically lower diffuse background levels in crowded areas. This may explain why GLIMPSEII stars are systematically brighter. It is possible that the higher GALCEN diffuse backgrounds would explain why the aperture photometry for the faintest sources show the greatest disagreement: with GALCEN magnitudes being fainter than the GLIMPSEII magnitudes. Examination of the GLIMPSEII residuals with regard to these faint source discrepancies (Fig. 9) show no conclusive evidence of systematic over-extraction on the part of GLIMPSEII.

If the GLIMPSEII extraction process is extracting a significant number of false sources then the GLIMPSEII diffuse background would be too faint resulting in GLIMPSEII magnitudes being too bright. GLIMPSEII extraction is done from the individual IRAC frame data. By inspecting the extracted sources from individual frames as compared to the mosaic image of the same area (the mosaic is the combined data from all frames for that given area of sky) it does not appear that GLIMPSEII is extracting a significant number of false sources. In fact, the mosaic images show additional real sources faint enough that they were neither detected nor extracted by GLIMPSEII or GALCEN.

We found that stars with the best GLIMPSEII to GALCEN agreement generally lie within or very close to dark clouds, where confusion is lowest.

As noted in the GALCEN paper (Ramirez et. al. 2008), they used two methods in determining source magnitudes: a PRF fitting method and an aperture photometric method. However the fluxes of the brightest sources were determined from a sub-array mode dataset. The GALCEN catalog indicates which method was used for the final quoted magnitude. By comparing the GLIMPSEII and GALCEN magnitudes by these various methods independently, one discovers where the largest disagreements occur. Large disagreements on the faint end are from matched sources where GALCEN used aperture photometry, while bright end disagreement occurred where GALCEN used sub-array mode data (see Fig. 2).

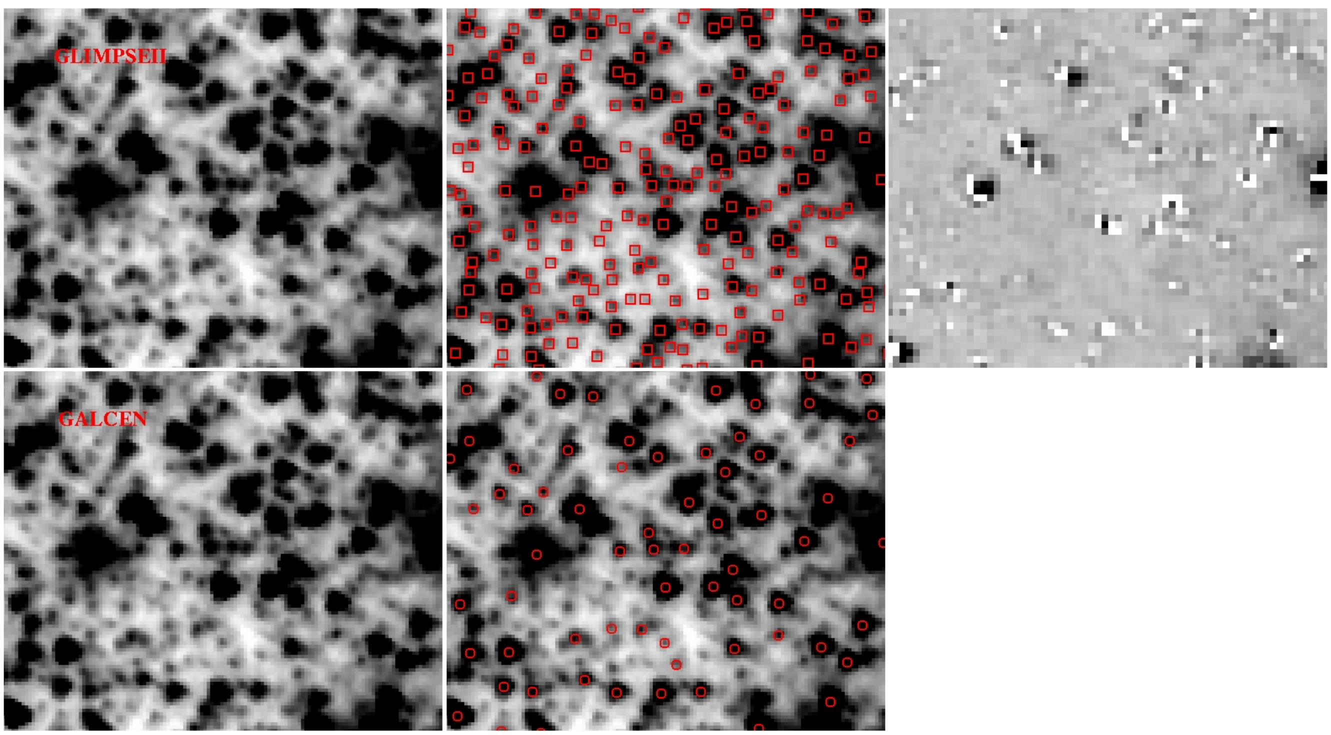

Figure 7: Comparison of IRAC[3.6] area extracted by GLIMPSEII versus the same area by GALCEN. The upper panels shows the GLIMPSEII results, the lower panels shows the GALCEN results. The left panels show the star field in reverse contrast. The center images show the marked sources listed in the GLIMPSEII Archive (top) versus the GALCEN catalog (bottom). The upper right hand panel show the resultant GLIMPSEII residual image. The location is l=0.34 b=-0.615. GLIMPSEII is more complete in finding and extracting sources. The GLIMPSEII residual image show the effect of the under-sampled channel 1 PRF which leads to greater peak-to-peak fluctuations around subtracted sources. The GLIMPSEII Archive is the more complete GLIMPSEII source list; it is used here to demonstrate the completeness of the GLIMPSEII extractions.

3.4 Bright Star Discrepancies

The bright-star discrepancies are a bit puzzling. IRAC channels 1 and 4 show the largest disagreements between GLIMPSEII and GALCEN magnitudes. GLIMPSEII did not process any of the sub-array mode data that GALCEN used and only did the comparison up to the 2 second frametime bright limits (GLIMPSEII estimates these to be 7.0, 6.5, 4.0 and 4.0 magnitude for IRAC[3.6], [4.5], [5.8], and [8.0] respectively). For IRAC[3.6], only within 0.5 magnitudes of the bright limit do we see the magnitude offset increase (see Fig. 3). IRAC [8.0] shows the worst disagreement. From magnitude 4 through roughly magnitude 8 there is a 0.2 magnitude difference between the GLIMPSEII and GALCEN magnitudes. GLIMPSEII residual images (see Fig. 8) reveal a relatively flat and clean residual image, with roughly equal numbers of pixels above and below baseline, no indication of improper source extraction.

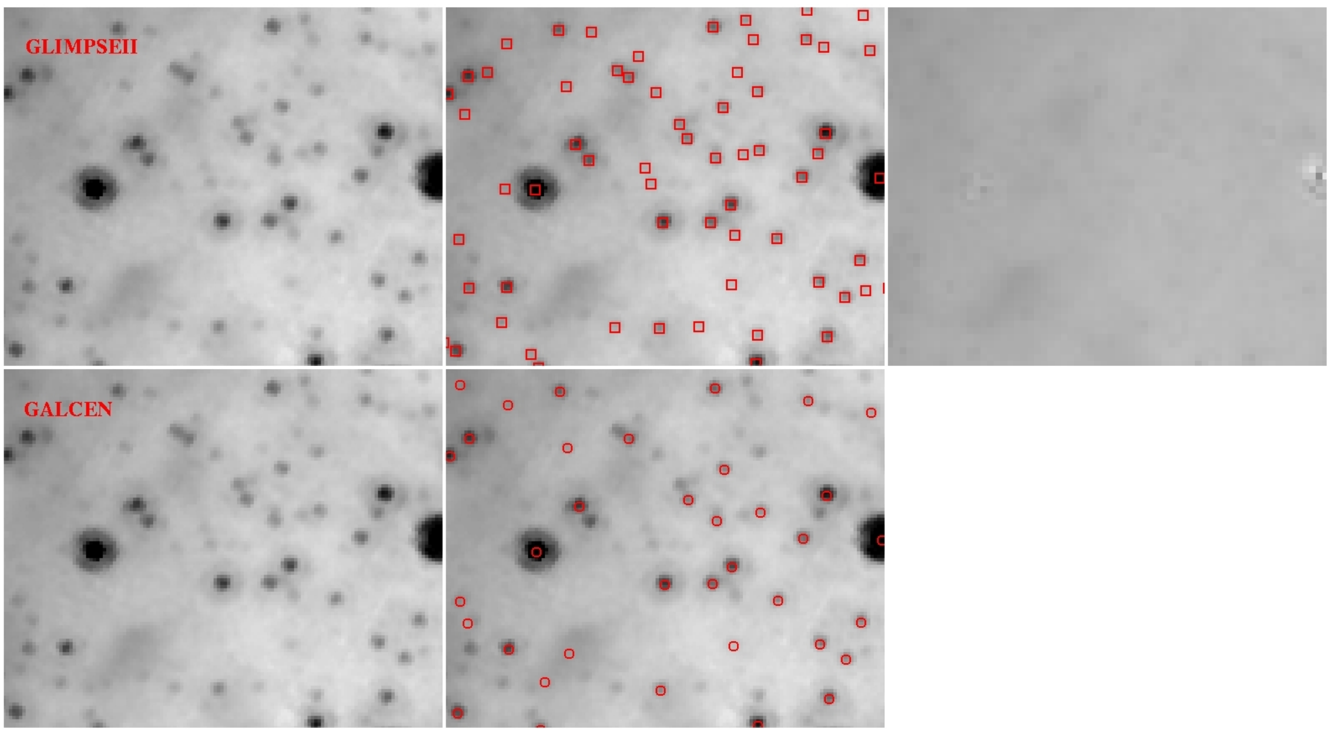

Figure 8: IRAC[8.0] data of the same star field as Fig.7. Note there is no evidence of over-extraction of point sources in GLIMPSEII residual.

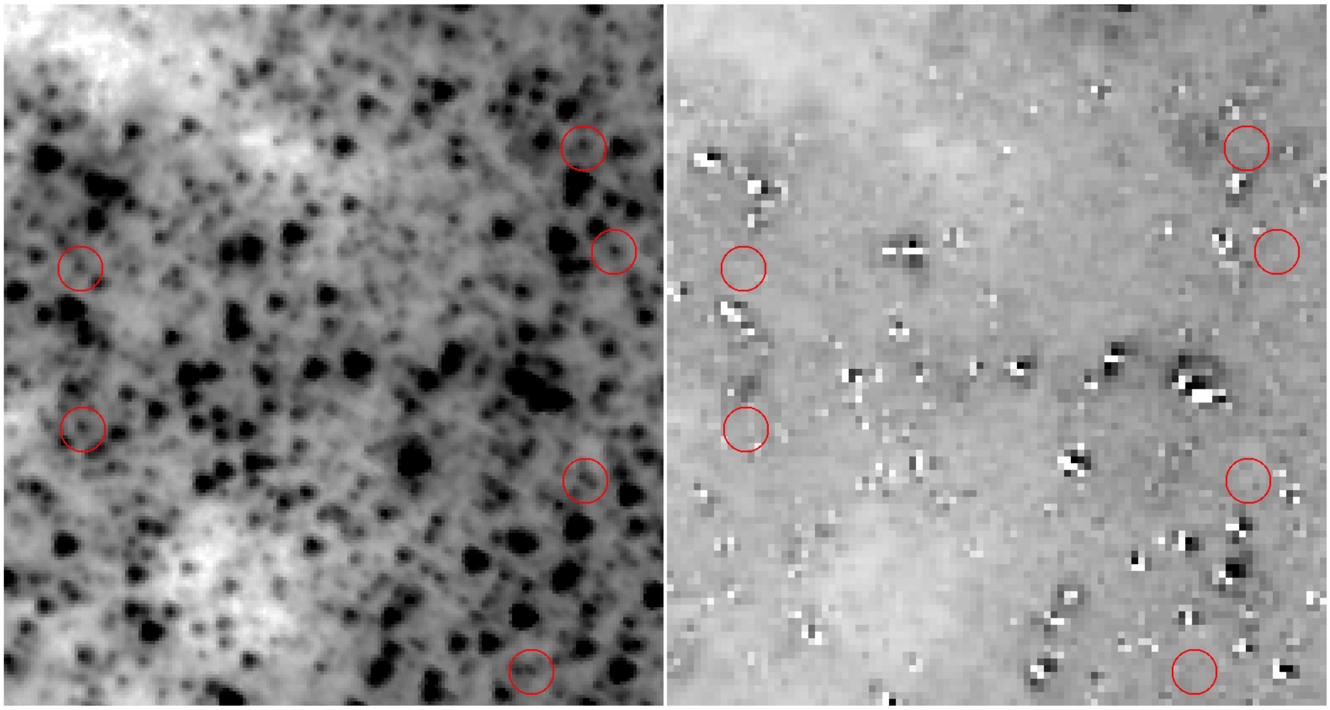

Figure 9: IRAC[3.6] data at Galactic longitude and latitude (0.32,-0.228), left panel shows star field in reverse contrast. Right panel shows the GLIMPSEII residual. Circled are 5 sources between magnitude of 12.0 and 13.0 and show a magnitude disagreement between the two catalogs of greater than 0.5 magnitudes. The GLIMPSEII residual show no evidence of over-extracting the source at these positions.

3.5 Comparison with Flux Calibration Sources

Examination of independent flux calibration sources confirm that there are no systematic magnitude offsets in the GLIMPSEII source lists. GLIMPSEII, as stated in GLIMPSEII v2.0 Data Release Document, observed 100 flux calibration sources and found no systematic offsets from the predicted magnitudes. Unfortunately only 2 of those calibrators lie within the GALCEN region. Agreement between the GLIMPSEII and GALCEN magnitudes for these 2 calibrators agree to within the uncertainties for the non-saturated data for all four channels except for the brighter IRAC[8.0] source which exhibits the roughly 0.2 magnitude offset between GALCEN and GLIMPSEII bright IRAC[8.0] magnitudes (Fig. 10). As a further check Figure 11 displays the plot for the roughly 25 flux calibrators within the inner 2 degrees of the Galactic center where we expect the source densities to be somewhat similar to the GALCEN data. This plot, as well as the full GLIMPSEII flux calibrator plot (Fig. 12) show that the GLIMPSEII magnitudes agree well throughout the magnitude range of 4 – 11 mags. We therefore suggest that the GALCEN IRAC[8.0] magnitudes for data brighter than roughly 8^{th} magnitude are too faint by approximately 0.2 magnitudes.

4 Conclusions

Analysis of GLIMPSEII photometric techniques in crowded fields is an ongoing process. Substantial parts of the GLIMPSEII and GALCEN regions, including those studied here, are probably at, if not beyond, the confusion limit. Concerning the agreement between the GALCEN and GLIMPSEII magnitudes there is general agreement in a limited magnitude range for each of the 4 IRAC channels at a level of about 10% uncertainty (which is much greater than the combined uncertainties of the two catalogs). These ranges are approximately magnitudes 7.5 to 10.5 for IRAC[3.6], 6.5 to 10.5 for IRAC[4.5], 6.0 to 10.0 for IRAC[5.8] and 8.0 to 10.0 for IRAC[8.0]. Fainter than these limits we see systematic offsets between the two catalogs that are much greater than 10% which get progressively worse. For brighter magnitudes in IRAC[3.6] and IRAC[8.0] we also see offsets greater than 10%.

We do believe the GALCEN uncertainties to be too small. We cannot account for magnitude offsets between the GALCEN and GLIMPSEII magnitudes for data in the range of 4 to 8 magnitudes where GLIMPSEII flux calibrators show GLIMPSEII magnitudes to be in good agreement with predictions. Since GLIMPSEII had access to a greater set of independently determined flux calibrators, and the GLIMPSEII magnitudes for those calibrators do not show any evidence of a systematic offset, we suspect that the SSC PRFs that GALCEN used may be responsible for the observed offsets. Inspection of GLIMPSEII residual images shows no indication of improper or systematic extraction problems. GLIMPSEII systematically finds sources to fainter limits. With a greater number of sources extracted from the GLIMPSEII images, the resultant GLIMPSEII background values are systematically lower than the GALCEN background values for extracted sources.

In regard to the GALCEN processing, as stated earlier, it has recently been determined that the PRFs provided by SSC for IRAC source extraction were not ideal due to the under-sampled nature of the IRAC point spread function (see: http://ssc.spitzer.caltech.edu/postbcd/mopex.html). It is likely that the lower uncertainties in the MOPEX PRF flux estimate published in the GALCEN survey are linked to these non-ideal PRFs. SSC is working to better characterize the IRAC PRF for future use with improved versions of MOPEX. For this reason the GLIMPSEII processing is viewed as an improvement on the GALCEN catalog and the larger GLIMPSEII uncertainties are more representative of the overall uncertainties of these measurements. The difficulty of performing photometry in the Galactic center should not be under-stressed. Accurate accounting of uncertainties are critical and not all photometric reduction packages process uncertainties in the same way. To date the GLIMPSE team has found the uncertainties produced by DAOPHOT to be robust and responsive to the complexities of the GLIMPSE, GLIMPSEII and GALCEN datasets, but we are continuing to evaluate and improve our uncertainty estimates.

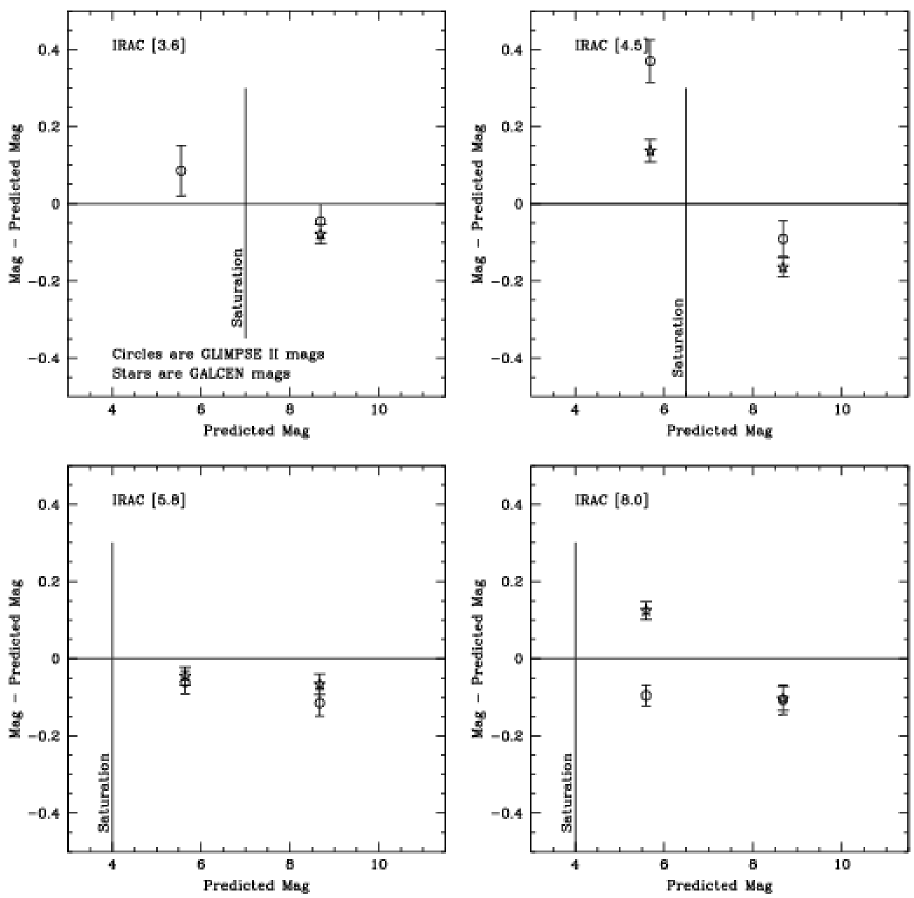

Figure 10: Plotted are the two GLIMPSEII flux calibrators which lie within the GALCEN area. Open Circles are GLIMPSEII data points, stars are GALCEN data points.

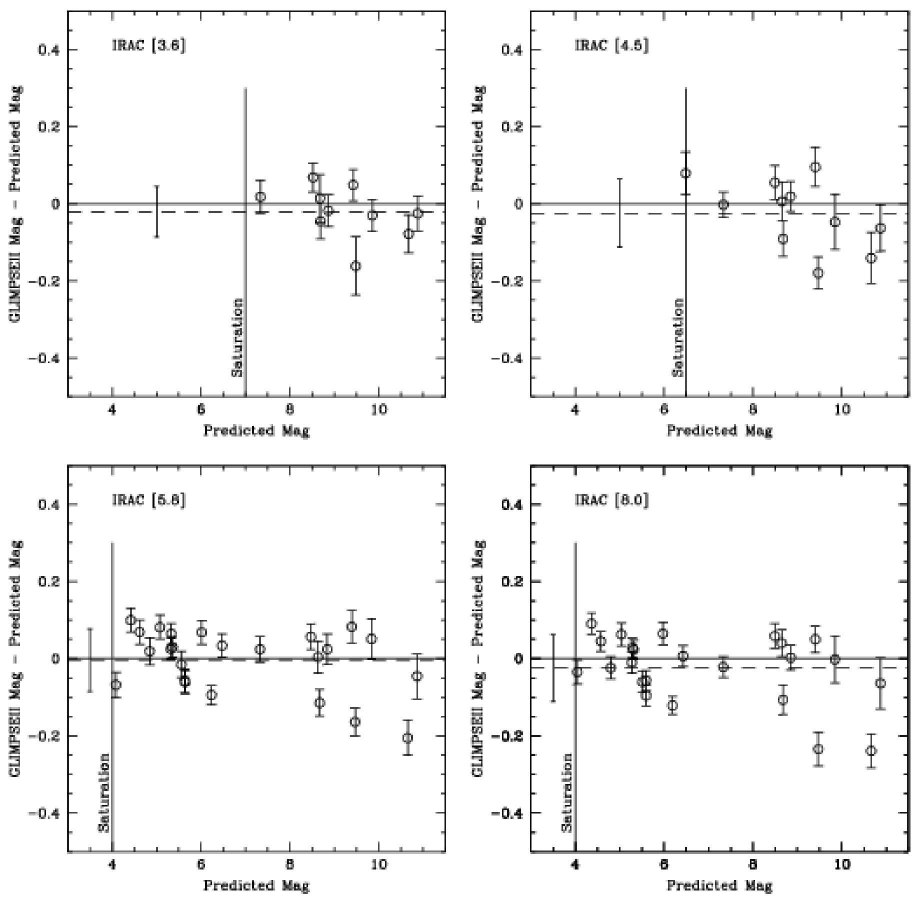

Figure 11: Plotted are the GLIMPSEII flux calibrators which lie within 2 degrees of the Galactic center. The dashed line indicates the average difference between the GLIMPSEII magnitude and the predicted magnitude. The error bar furthest to the left is the RMS of the plotted data points that produced the dashed line.

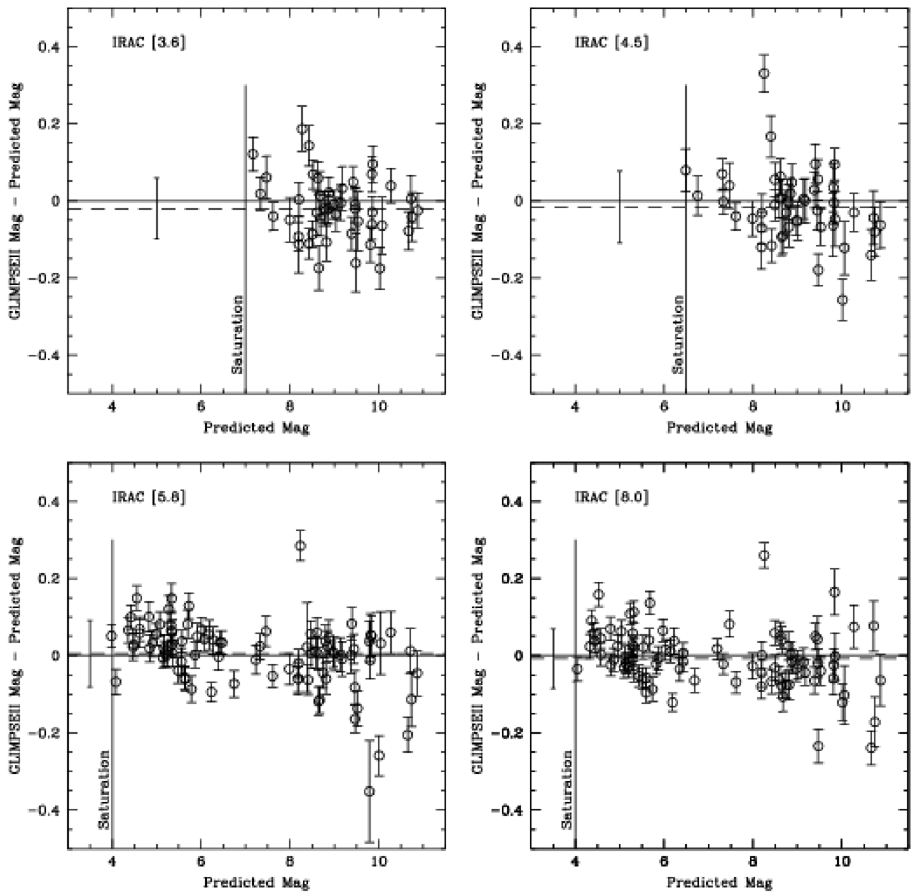

Figure 12: GLIMPSEII flux calibrators for the entire GLIMPSEII region. The dashed line indicates the average difference between the GLIMPSEII magnitude and the predicted magnitude. The error bar furthest to the left is the RMS of the plotted data points that produced the dashed line.