

WHIRC Report V – Photometric Precision

Dick Joyce
14 October 2008

1. Analysis of Standard Star Data from Hunt et al.

The photometric and flatfielding performance was tested on the open cluster NGC 7790, which has six standard stars included in the listing of Hunt et al. (1998 AJ, 115, 2594) as AS 40. This field was imaged through six filters (J, H, Ks, PaB, FeII, BrG) to test the performance in both wide- and narrow-band filters on the night of 19 September 2008 UT. Nine images were taken in each filter, in a 3×3 grid pattern on 30 arcsec centers. The integration times were 4s and 40s for the wide- and narrow-band filters, respectively.



Figure 1: WHIRC J band image of the open cluster NGC 7790. The six stars from Hunt et al. are noted. The results from star 5 were rejected because the published magnitudes included the faint companion which is easily resolved in this image.

All of the data were reduced in the same manner. Since all were taken in Fowler1 mode, no rescaling was necessary:

- Preparation: trim frames to 2048×2048 ; linearize with `irlincor` using $A = 1.000$, $B = 0.004227$, $C = 0.02691$
- Average all frames in each filter with median filtering to generate a sky frame
- Subtract the sky frame from each input frame to yield a (unflattened) sky-subtracted image
- Divide each sky-subtracted image by a normalized dome flat to yield a flattened image. NOTE: *The flatfield images do not incorporate correction for the pupil ghost.*

The six Hunt stars in each image were then measured using the task `phot`, with apertures of 1.5 and 2.0 arcsec radius and a sky reference annulus from 2.0 to 3.0 arcsec radius. This was done for both the unflattened and flattened images. The difference between the phot magnitude (the number of sky-subtracted counts within the extraction aperture normalized to a magnitude scale) and the published magnitude from Hunt et al. was calculated. If there were no errors in the instrument, flatfielding, or published magnitudes, this number should ideally be the same for all measurements in a given filter, so the variations are a measure of the statistical uncertainty (assuming, of course, photometric sky conditions). NOTE: The results for the 3.0 and 4.0 arcsec diameters were virtually identical, so only the 3.0 arcsec data will be summarized here for clarity.

Two approaches to analysis were carried out, each of which addresses somewhat different aspects of the performance:

- For each star, the [phot – published] magnitudes in the nine sky positions are averaged and the standard deviation of the mean calculated. This measures the accuracy of flatfielding, but assumes photometric conditions; the accuracy of the published magnitudes is not important.
- For each image, the standard deviation of the [phot – published] magnitudes for the six stars is calculated for each telescope pointing; we then calculated the average over the nine sky positions. Since the six stars are in different positions on the detector, this is also a measure of the flatfielding accuracy, but does not require photometric conditions; however, any error in the published magnitudes will contribute to the calculated uncertainty.

Standard Stars

The NGC 7790 (AS40) field contains six standard stars in the Hunt et al. catalog. Their broadband magnitudes, as well as those from the 2MASS Point Source Catalog (PSC), are shown in Table 1 below:

Table 1: Hunt et al. and 2MASS Standards in NGC7790

star		J	H	Ks
0	Hunt	11.051	10.408	10.240
	2MASS	11.010	10.336	10.229
1	Hunt	11.900	11.097	10.861
	2MASS	11.919	11.137	10.884
2	Hunt	11.477	10.569	10.314
	2MASS	11.468	10.504	10.313
3	Hunt	10.578	9.966	9.785
	2MASS	10.602	9.943	9.787
4	Hunt	10.356	9.695	9.516
	2MASS	10.337	9.653	9.500
5	Hunt	9.488	9.418	9.405
	2MASS	9.496	9.432	9.447

The published uncertainties for these standards are in the range 0.008 – 0.018 for the Hunt et al. catalog and 0.015 – 0.030 for the 2MASS catalog. This analysis will use the Hunt et al. numbers because of their lower uncertainty. **NOTE:** Star 5 is problematical because it is sufficiently bright to push the WHIRC detector close to saturation, particularly in the broadband filters. It also has a companion approximately 3.2 magnitudes fainter only 3.5 arcsec away, *which was included in both the Hunt et al. and 2MASS apertures* (whereas it was easily isolated in the WHIRC images). In fact, the data show that the results for this star were typically 0.03 – 0.05 mag fainter than for the other stars, consistent with the published magnitudes being too bright. As a result, we present results for both the inclusion and exclusion of star 5 from the dataset, *but emphasize the latter as our conclusions for this experiment.*

Method 1—Sky Position Averaging

The results for the sky position averaging are presented in Table 2 below. As noted above, the input data are the difference between the phot magnitudes (measured in a 3 arcsec diameter aperture with sky subtraction) and the magnitudes published in Hunt et al.

The three entries for each star/filter combination are: the mean value of the differences for the flattened images; the standard deviation of the mean for the unflattened images; the standard deviation of the mean for the flattened images. The two right-hand columns are the averages of these numbers for all of the six stars and for stars 0-4. Since we know the published magnitudes for star 5 to be unreliable, the last column, and in particular the averaged sigma for the stars 0-4, represents the conclusions of this experiment.

Table 2: Results for Sky Position Averaging

		star0	star1	star2	star3	star4	star5	all	stars 0-4
J	mean	1.977	1.986	1.997	2.013	2.006	2.057	2.006	1.996
	sd noflat	0.026	0.026	0.092	0.025	0.013	0.038	0.039	0.035
	sd flat	0.019	0.018	0.007	0.015	0.009	0.019	0.028	0.015
H	mean	1.892	1.900	1.929	1.916	1.926	1.980	1.929	1.913
	sd noflat	0.030	0.029	0.087	0.050	0.041	0.039	0.040	0.036
	sd flat	0.020	0.019	0.010	0.014	0.011	0.044	0.031	0.016
Ks	mean	2.503	2.505	2.518	2.521	2.518	2.527	2.515	2.513
	sd noflat	0.019	0.037	0.086	0.048	0.019	0.041	0.029	0.030
	sd flat	0.031	0.019	0.010	0.021	0.015	0.016	0.009	0.008
PaB	mean	4.499	4.489	4.494	4.533	4.518	4.656	4.532	4.507
	sd noflat	0.260	0.019	0.059	0.109	0.024	0.022	0.054	0.043
	sd flat	0.016	0.022	0.011	0.014	0.009	0.021	0.063	0.018
Fell	mean	5.024	5.022	5.041	5.042	5.037	5.084	5.042	5.033
	sd noflat	0.028	0.022	0.056	0.103	0.034	0.020	0.040	0.043
	sd flat	0.010	0.025	0.006	0.013	0.008	0.028	0.022	0.010
BrG	mean	5.415	5.428	5.407	5.416	5.419	5.453	5.426	5.417
	sd noflat	0.022	0.024	0.074	0.114	0.040	0.015	0.033	0.036
	sd flat	0.025	0.040	0.009	0.011	0.010	0.019	0.022	0.008

Method 2 – Star Averaging

The results for the averaging over the standard stars for each telescope pointing are given below in Table 3. The results are the standard deviation of the mean results for stars 0 – 4 only for each of the nine pointings. Both the unflattened and flattened images are summarized. The final row is the average of these standard deviations, with the flattened data representing the conclusions of this experiment.

Table 3: Results for Star Averaging

position	J		H		K		PaB		Fell		BrG	
	noflat	flat										
1	0.080	0.011	0.074	0.012	0.070	0.005	0.102	0.025	0.098	0.009	0.107	0.009
2	0.023	0.013	0.017	0.017	0.025	0.031	0.331	0.016	0.048	0.008	0.052	0.009
3	0.026	0.026	0.021	0.024	0.039	0.032	0.030	0.028	0.031	0.022	0.021	0.013
4	0.096	0.014	0.081	0.008	0.073	0.005	0.104	0.016	0.103	0.012	0.094	0.042
5	0.029	0.010	0.029	0.016	0.025	0.010	0.050	0.013	0.052	0.010	0.042	0.026
6	0.049	0.026	0.035	0.026	0.044	0.021	0.038	0.024	0.034	0.022	0.022	0.013
7	0.105	0.014	0.088	0.017	0.086	0.012	0.120	0.020	0.095	0.014	0.116	0.029
8	0.023	0.017	0.073	0.022	0.018	0.020	0.057	0.016	0.061	0.019	0.067	0.009
9	0.034	0.024	0.035	0.024	0.031	0.031	0.031	0.027	0.027	0.022	0.021	0.017
avg	0.052	0.017	0.050	0.018	0.046	0.018	0.096	0.020	0.061	0.015	0.060	0.019

Dimples

Table 2 shows clearly that for some stars, there is a very significant difference between the standard deviation results for the unflattened and flattened data. Much of this is probably a result of unusual detector artifacts. A typical flatfield image (Figure 2) shows numerous circular features which appear to be array defects. The cause of these features is unknown. However, it is important to realize that these are not dead pixels, but regions of depressed sensitivity which still respond linearly to radiation; as a result, they can be largely corrected by flatfielding (Figure 2). The system sensitivity within these regions is, of course, reduced.

The measured flux from a star which falls on one of these regions will be significantly reduced in unflattened images, but relatively unaffected in the flattened images. This is probably the greatest contribution to the higher sigma in the unflattened images and explains why only some stars were affected.

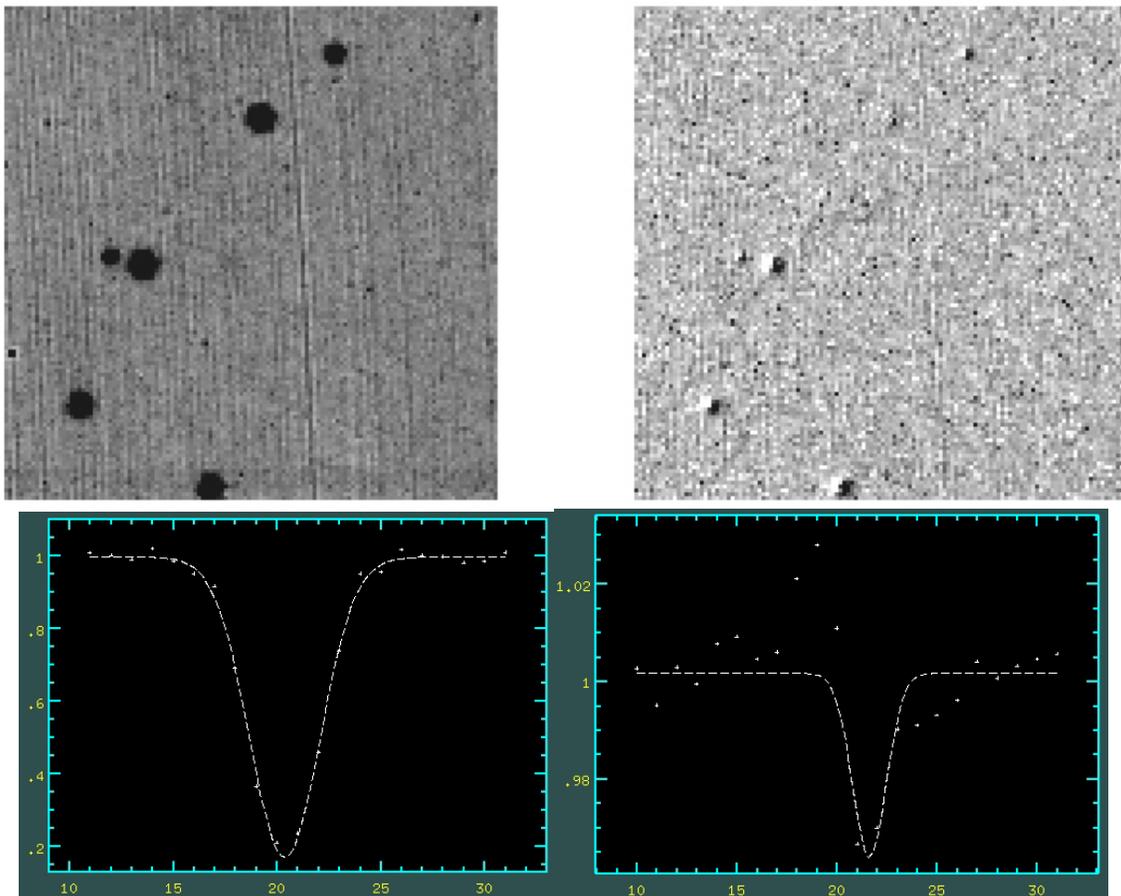


Figure 2: (top left): 128×128 subimage of an H-band dome flat, showing the normal “tree-ring” structure and the circular, apparently dead features. A line plot through one of the spots (lower left) shows that the features are not dead pixels, but regions of reduced responsivity. The ratio of two separate flatfields taken five months apart (top

right) shows that the features are quite stable over long periods to within a few percent (lower right).

Conclusions

Both experiments indicate that flatfielded data, even without correction for the pupil ghost, yield photometrically accurate results in the 1 – 2 % range for both broad- and narrow-band filters. The results for position averaging are somewhat better than those for star averaging, possibly reflecting the inherent uncertainty in the standard star magnitudes, which are in the 0.8 – 1.8% range for the Hunt et al. standards. The lack of pupil correction may not have substantially affected the final results, since the pupil ghost is significant over only a 200×200 pixel region near the center of the array and would have affected the results for at most one of the nine telescope pointings in the experiment.

2. Analysis of 2MASS Standards

In a second approach to analyzing the photometric precision, the NGC 7790 data were reduced in the same manner as employed for science observations, combining the nine separate frames into a single image following the steps below. This was done only for the H band data. The first four steps were the same as those carried out for the individual frame analysis in section 1.

- Preparation: trim frames to 2048×2048 ; linearize with `irlincor` using $A = 1.000$, $B = 0.004227$, $C = 0.02691$
- Average all frames in each filter with median filtering to generate a sky frame
- Subtract the sky frame from each input frame to yield a (unflattened) sky-subtracted image
- Divide each sky-subtracted image by a normalized dome flat to yield a flattened image. NOTE: *The flatfield images do not incorporate correction for the pupil ghost.*
- Use the IRAF task `xyget` to determine X and Y offsets for common stars in all nine images.
- Use the IRAF task `zget` to determine the median sky level in each frame and subtract to eliminate offsets.
- Use the IRAF task `nircombine` to combine the frames into a single image. Because no distortion correction was carried out, the stellar images in the combined frames are slightly elongated at the edge of the field. Therefore, an average rather than a median was used in the combining to hopefully preserve the flux.
- Download the 2MASS point source catalog overlay and pick ~ 15 well-placed unconfused stars to recalculate the WCS information on the averaged frame using the task `cmap`. As shown in Figure 3, the 2MASS source positions agree very well with most of the stars in the combined WHIRC image.

- The 2MASS celestial coordinates were converted to X, Y coordinates in the image using the task cctran and the fiducial positions and plate scales of the image. These were put into a coordinate file for the phot task.
- The task phot was run for apertures of 2, 3, and 4 arcsec diameter. Because some of the stellar images were elongated as noted above, the 2 arcsec results differed quite a bit from the 3 and 4 arcsec results; the 3 arcsec results were used.
- The counts from the phot results were converted to a magnitude scale and subtracted from the 2MASS PSC H band magnitudes. An offset of 25 was used to put the differences near a value of zero. These differences were then plotted as a function of the 2MASS magnitude (Figure 4).

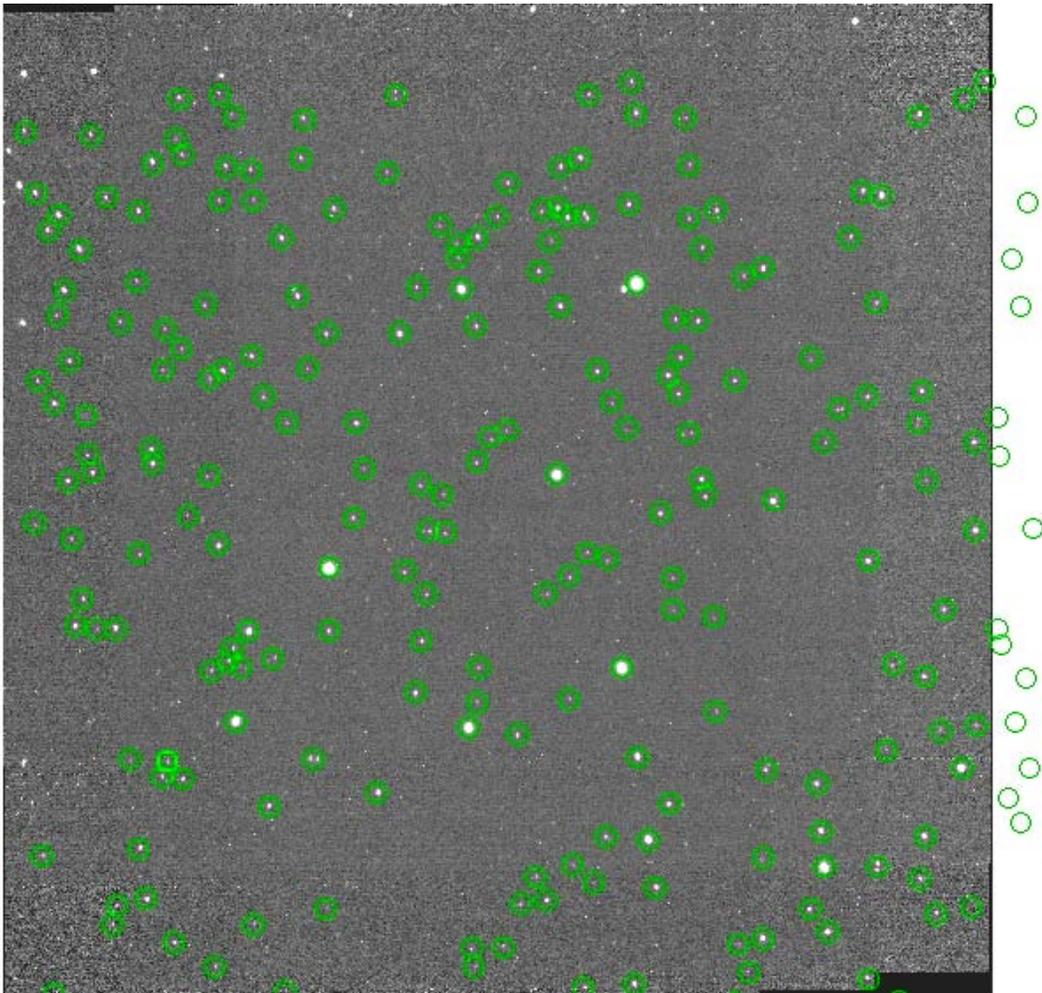


Figure 3: Combined H band image of the NGC 7790 field using the nine individual frames shifted to coalign the stars. The 2MASS point sources (green circles) are overlaid on the image. Note that several 2MASS point sources are actually multiple sources at the higher spatial resolution of WHIRC.

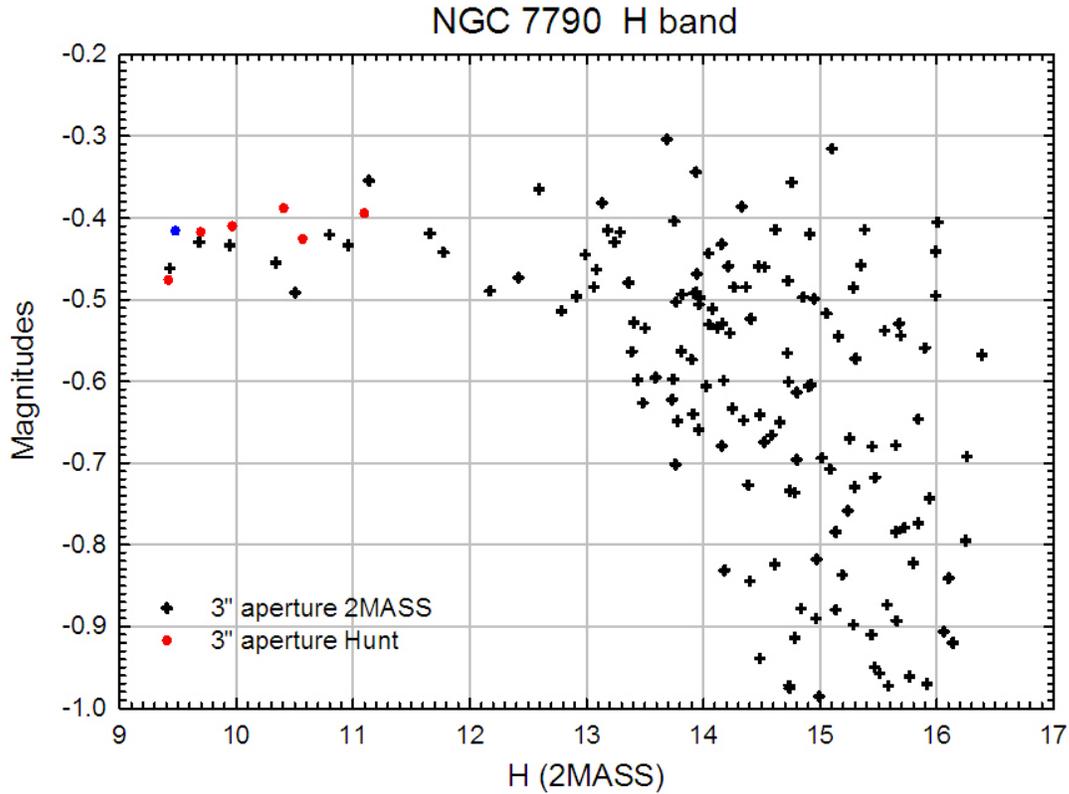


Figure 4: Plot of the $[2MASS - phot]$ magnitudes for the 2MASS sources in the NGC 7790 WHIRC image vs. the 2MASS H magnitude (plus points). The red circles use the H band magnitudes from Hunt et al. for the six sources in the field. The blue circle uses the Hunt et al. magnitude corrected for the flux from the companion to star 5.

Discussion

As expected, the points in Figure 4 show the scatter in the difference values increases significantly for fainter sources. The formal errors in the 2MASS catalog are typically 0.03 – 0.04 mag for sources with $H < 13$, 0.04 – 0.05 for $13 < H < 14$, and ~ 0.1 for $H \sim 15$. The expected peak-to-peak envelope is probably three times these values. The somewhat larger differences, particularly in the negative direction, for the fainter sources are probably a result of confusion, where multiple sources on the WHIRC image are contained within a single 2MASS source measurement. In such a case, the phot task will centroid on the brighter source and measure only its flux, unless they are separated by less than 1.5 arcsec.

As shown in Table 1, there are significant (up to 0.05 mag) differences between the six sources common to 2MASS and the Hunt et al. catalog. The formal errors quoted by Hunt et al. are approximately half those in the 2MASS catalog, from 0.008 to 0.018 mag, so it is not impossible for statistical differences as large as 0.05 mag to occur. Both Hunt et al. and 2MASS included both components of star 5 (Figure 1). Measurements of both the brighter star and its companion on the WHIRC image yielded a difference of 3.19 mag, so the brighter source itself is 0.06 mag fainter than both together.

The differences [Hunt et al. - phot] are plotted in Figure 4 as red circles. The differences between the Hunt et al. and 2MASS magnitudes are evident, as is the tighter distribution of the points using the Hunt et al. values. When the corrected flux for the bright component of star 5 is used (blue circle), the correlation is even better. Table 4 presents the statistics of the scatter in the values.

Table 4: Standard Deviation of Scatter in Magnitude Differences

Sources	Number	Magnitude	Sigma (mag)
2MASS, H < 14	47	2MASS PSC	0.089
Hunt et al.	6	2MASS PSC	0.046
Hunt et al.	6	Hunt et al.	0.031
Hunt et al., star 5 corrected	6	Hunt et al.	0.014

Conclusions

Along with the results from section 1, this experiment demonstrates that photometric precision $\sim 2\%$ is possible with WHIRC. The results presented here may improve slightly once the pupil ghost correction is implemented; however, the relatively wide grid spacing of these observations minimizes the effect of the pupil ghost on the combined image.

The ability to characterize the performance of WHIRC to better than this level is limited by the accuracy of the published standard star catalogs. The 2MASS PSC provides a large, all-sky database, although the formal errors for any one source can be 0.03 – 0.04 mag, as noted above. The list of Hunt et al. traces its calibration to the UKIRT Faint Standards list (Casali & Hawarden 1992, JCMT-UKIRT Newsletter, 4, 33), which has been expanded (Hawarden et al. 2001, MNRAS, 325, 563). Both of the UKIRT lists claim typical uncertainties ≤ 0.01 mag.

Color terms may be important for red stars in the J and Ks bands. The MKO H band filter in WHIRC is quite similar to that used at UKIRT, but the J band filter is significantly narrower, and the Ks filter has a significantly shorter cutoff wavelength than the K filter used for the UKIRT and ARNICA measurements.