Mon. Not. R. Astron. Soc. **380,** 1433–1439 (2007)

doi:10.1111/j.1365-2966.2007.12100.x

Improved SAAO–2MASS photometry transformations

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Accepted 2007 June 12. Received 2007 June 6; in original form 2007 March 12

ABSTRACT

Near-infrared photometry of 599 stars is used to calculate transformations from the South African Astronomical Observatory (SAAO) *JHK* system to the Two-Micron All-Sky Survey (2MASS) JHK_S system. Both several-term formal regression relations and simplified transformations are presented. Inverse transformations (i.e. 2MASS to SAAO) are also given. The presence of non-linearities in some colour terms is highlighted.

Key words: techniques: photometric – infrared: general.

1 INTRODUCTION

The *JHK* observations on which this paper is based were obtained in order to supplement optical photometry of two groups of stars, namely potential red standard stars (M dwarfs and giants) and nearby stars (with distances deduced from *Hipparcos* parallaxes). The individual infrared (IR) measurements will be reported elsewhere together with the optical photometry, but here the data are put to the use of deriving accurate transformations between the South African Astronomical Observatory (SAAO) *JHK* and Two-Micron All-Sky Survey (2MASS – Skrutskie et al. 2006) JHK_S systems.

To the best of the authors' knowledge, the transformation between the 2MASS and SAAO near-IR photometric systems has only been discussed by Carpenter (2001), with an update on the website http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec6_4b.html. Carpenter (2001) based his formulae for the transformation of SAAO photometry to 2MASS K_S, $(J-H)$, $(H-K_S)$ and $(J-K_S)$ on data for 94 stars. The updated relations used data for 114 stars. By combining the new SAAO photometry mentioned above with existing measurements of SAAO IR standards (Carter 1990; Carter & Meadows 1995), we are able to increase the number of available data to 599. This allows us to produce more accurate transformation equations, and also to highlight features which are not very evident in the smaller data set used by Carpenter (2001).

The new SAAO observations are briefly described in Section 2, and the data preparation in Section 3. Section 4 deals with the transformations from SAAO magnitudes and colours to 2MASS values, while the inverse transformations are given in Section 5. Conclusions are presented in the last section of the paper.

2 OBSERVATIONS

All measurements were made with the Mk II IR photometer mounted on the 0.75-m telescope at the Sutherland site of SAAO. The instrument is an upgrade of the very similar Mk I photometer described in Glass (1973).

Observing modules consisted of 10-s integrations on the target, 20 s on the nearby sky, followed by a further 10 s on the star. A single module gave sufficient accuracy (see below) for stars brighter than fourth magnitude; more modules were used for fainter stars (usually two for *JHK*, up to six for *L*). In order to keep track of zero-point changes, every third or fourth star observed was a standard (typically at hourly intervals). A 36-arcsec-diameter aperture was used throughout.

Since online reductions were available, atmospheric conditions were continuously monitored and observing restricted to perfectly photometric weather.

Attempts were made to obtain *JHK* photometry for all programme objects, and *L* for brighter targets ($L < 6$). To these data we add the *JHK* magnitudes of 302 SAAO IR standards as given in Carter (1990) and Carter & Meadows (1995).

All standard star measurements (numbering more than 2000) obtained during the 4 yr spanned by our observations were used to check for the presence of colour dependencies of observed magnitudes. None was found. Since the telescope, instrument, and filters are the same

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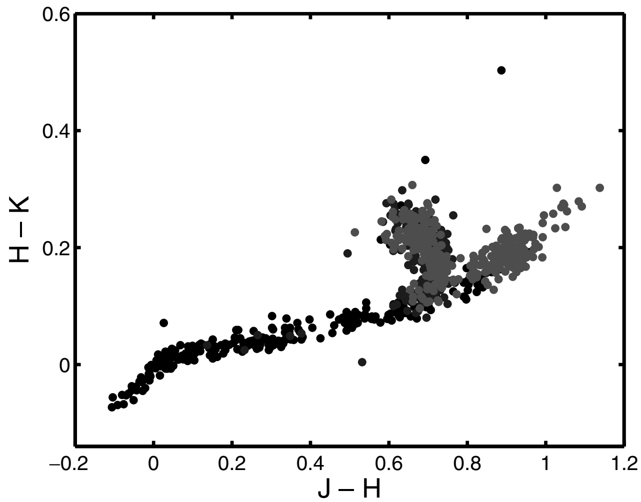

Figure 1. A colour–colour diagram based on photometry of SAAO IR standard stars (black), stars with large *Hipparcos* parallaxes (blue) and red candidate standard stars (red).

as those used by Carter (1990) and Carter & Meadows (1995); this is perhaps not surprising. The conclusion is that the measurements are indeed on the SAAO IR system.

3 DATA

A preliminary comparison of the 2MASS and SAAO photometry was made in order to weed out stars for which there were large discrepancies (differences larger than 0.4–0.5 mag). This led to the removal of nine objects. In all cases but three, reasonable explanations for the discrepancies could be found – the presence of bright, very close companions (which would have affected the SAAO photometry in particular); or known variability. The three remaining stars are faint, and may have been misidentified at SAAO.

A further seven stars are excluded: four of these have incomplete photometry (no J measurements), and two are known variables with large scatter in their SAAO photometry. The seventh is the SAAO IR standard YLW 36, which is by far the reddest star in the group ($J - H = 1.776$, $H - K = 0.968$, $J - K = 2.744$). The data for YLW 36 were included by Carpenter (2001), and are clearly visible as extreme outliers in his plots (fig. 12). Since the star is almost a magnitude redder in $J - H$, and more than a magnitude redder in $J - K$ than all other stars in the samples, it has an exaggerated influence on any regression relation involving colours.

The numbers of remaining stars are 301 IR standards, 236 with large parallaxes, and 399 candidate red standards – 936 in total. A visual impression of the general accuracy of the SAAO photometry can be gained by an inspection of the $(J - H, H - K)$ diagram in Fig. 1. Duplicate measurements were obtained for 331 out of the 636 large-parallax and candidate-standard stars, allowing a quantitative assessment of the accuracy: only 16 measurements had scatter in excess of 0.03 mag. Fig. 2 is a histogram of the standard deviations of repeated measurements.

The differences between the 2MASS and the SAAO photometric measurements are plotted in Fig. 3, for each of the filters. For the brightest stars the central parts of the 2MASS images were saturated; hence, the photometric accuracy is low (Skrutskie et al. 2006). In what follows attention is therefore restricted to stars with (SAAO) magnitudes $J \geqslant 5.5$, $H \geqslant 5.2$ and $K \geqslant 4.6$: the differences between 2MASS and SAAO photometry for these stars are plotted in Figs 4–6. [These limits are about a magnitude fainter than the "saturated 'Read 1' " values given in http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec4_4d.html.]

An inspection of the plots shows the presence of a number (13) of outliers. Almost all of the nine upper outliers can be explained in terms of poor 2MASS photometry (influenced by diffraction spikes), known variability and/or the presence of close companions. One of the lower outliers corresponds to the photometry of a known flare star (which could conceivably show IR variability because of the presence of star-spots); in none of the remaining three cases could any plausible explanation for the discrepancies in photometry be found. In any case, these data are clearly unusual and are therefore excluded in the analysis.

Finally, since colour terms may be important in the transformations, it is best to include only measurements which simultaneously satisfy all three the magnitude restrictions given above. This leaves data for a total of 599 stars. The colour intervals covered are $-0.043 \leqslant (J - H) \leqslant 0.992$; $-0.087 \leqslant (J - K) \leqslant 1.390$ and $-0.044 \leqslant (H - K) \leqslant 0.503$. It goes without saying that extrapolation beyond these limits may be risky.

4 TRANSFORMATION RELATIONS

The transformations were determined by application of a step-wise multiple regression method (e.g. Seber 1977). This proceeds by adding one extra independent variable at a time to the regression. The added variable is, of course, that which gives the largest improvement (as

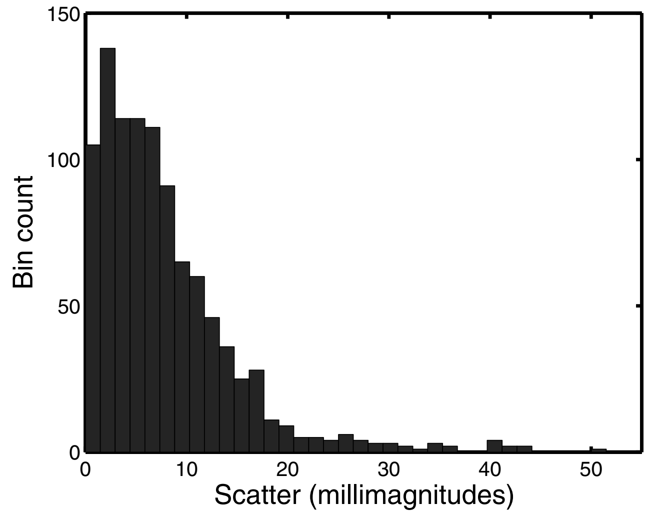

Figure 2. The distribution of standard deviations of repeated SAAO photometric measurements.

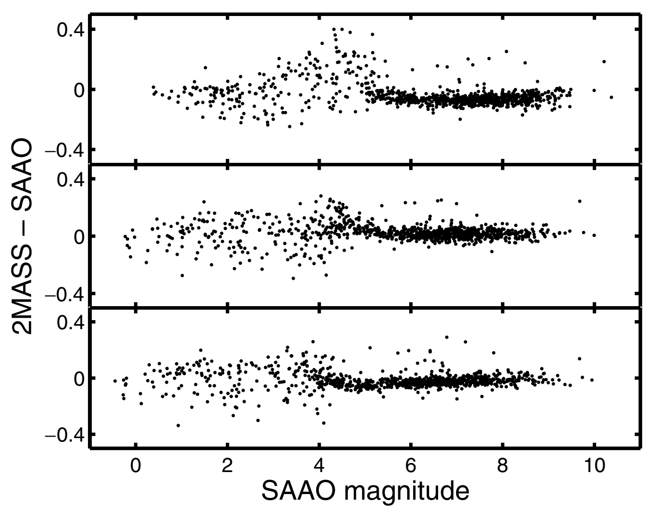

Figure 3. Differences between 2MASS and SAAO photometry for each of the stars, plotted against the SAAO photometry. From top to bottom panel, *J*, *H* and *K*.

measured by an entry *F* statistic) in the model fit. The improvement has to exceed a minimum level, otherwise no new variables are added. Before considering the next addition, each variable already in the model is re-evaluated, and the 'weakest' (according to an exit *F* statistic) eliminated if sufficiently poor. The pool of potential independent variables used were the three magnitudes *J*, *H* and *K*, the three colours $J-H$, $H-K$, $J-K$, and the squares of the colours.

The formal results for the magnitudes are

$$J_{\mathrm{2MASS}} = -0.028(0.003) + J - 0.047(0.004)(J-K) \quad \sigma = 0.026,$$
$$H_{\mathrm{2MASS}} = 0.014(0.001) + H \quad \sigma = 0.029,$$
$$K_{\mathrm{2MASS}} = -0.015(0.003) + K - 0.082(0.007)(J-H)^2 + 0.177(0.019)(H-K) \quad \sigma = 0.026, \tag{1}$$

where the unsubscripted variables on the right-hand side are measured in the SAAO system. The estimated standard errors are given in brackets following each coefficient.

For the colours,

$$(J-H)_{\mathrm{2MASS}} = -0.047(0.004) + 0.948(0.005)(J-H) \quad \sigma = 0.029,$$
$$(H-K)_{\mathrm{2MASS}} = 0.037(0.003) + 0.685(0.028)(H-K) + 0.072(0.007)(J-K)^2 \quad \sigma = 0.030,$$
$$(J-K)_{\mathrm{2MASS}} = 0.802(0.029)(J-K) + 0.480(0.108)(J-H)^2 - 0.238(0.074)(J-K)^2 + 0.425(0.156)(H-K) \quad \sigma = 0.026. \tag{2}$$

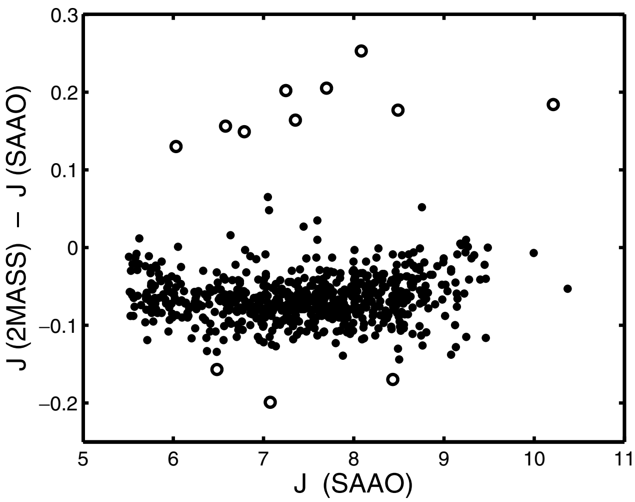

Figure 4. Differences between 2MASS and SAAO *J*-band photometry for the fainter stars, plotted against the SAAO photometry. Photometry of stars with consistently outlying data is plotted as the open circles.

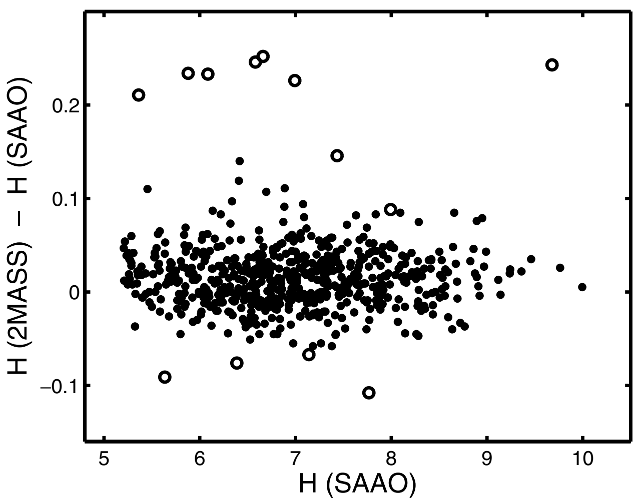

Figure 5. The same as that for Fig. 4, but showing *H*-band photometry.

All the coefficients in the expressions above are highly significant. Furthermore, tests involving information criteria (e.g. Burnham & Anderson 2004) and the well-known Mallow's C_p criterion (e.g. Draper & Smith 1981) confirmed that none of the models is overspecified in terms of the number of parameters used. None the less, in practical terms an increase of a few millimagnitudes in the residual scatter may be tolerated in order to obtain less-complicated transformations. Simplified relations, containing at most three terms, and involving minimal increases ($\leqslant$ 5 mmag) in σ are therefore also given for K, $(H - K)$ and $(J - K)$:

$$\begin{aligned} K_{2\mathrm{MASS}} &= K - 0.050(0.005)(J - H)^2 \qquad \sigma = 0.028, \\ (H - K)_{2\mathrm{MASS}} &= 0.046(0.003) + 0.944(0.018)(H - K) \qquad \sigma = 0.032, \\ (J - K)_{2\mathrm{MASS}} &= 0.859(0.007)(J - K) + 0.156(0.013)(J - H)^2 \qquad \sigma = 0.026. \end{aligned} \tag{3}$$

The following three remarks are worth making.

(i) In the cases of the H and $(J - K)$ transformations, the intercepts are not significant; hence the relations for zero intercepts are given. The same applies to the simplified K-transformation.

(ii) The standard errors of the coefficients may be considerably smaller in the simplified relations.

(iii) Due to their strong interrelatedness, the variables appearing in the full relations (1) and (2) could change with small changes in the data used.

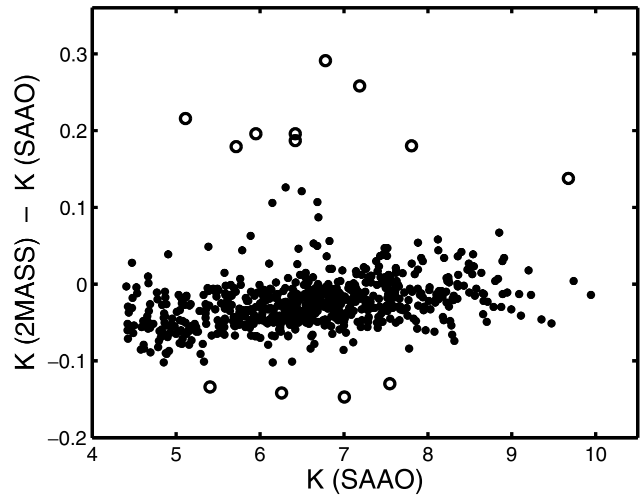

Figure 6. The same as that for Fig. 4, but showing *K*-band photometry.

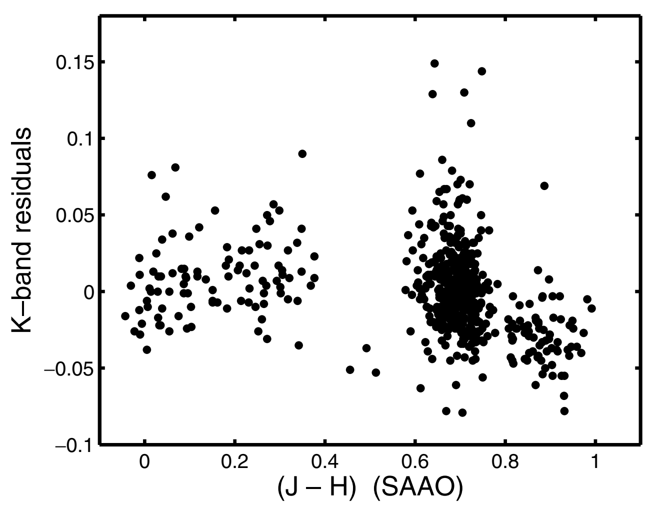

Figure 7. The dependence on $(J - H)$ of the residuals of the two-term *K*-band transformation in equation (7).

The above relations should, of course, be compared to the updated transformations on the 2MASS website:

$$\begin{aligned} K_{\mathrm{2MASS}} &= -0.024(0.003) + K + 0.017(0.006)(J - K), \\ (J - H)_{\mathrm{2MASS}} &= -0.048(0.006) + 0.944(0.017)(J - H), \\ (H - K)_{\mathrm{2MASS}} &= 0.043(0.003) + 0.945(0.026)(H - K), \\ (J - K)_{\mathrm{2MASS}} &= -0.005(0.006) + 0.944(0.012)(J - K). \end{aligned} \tag{4}$$

The $(J - H)$ and $(H - K)$ equations agree very well with the simplified transformations in equations (2) and (3). The $(J - K)$ transformations differ: fitting a relation of the same form as in equation (4) to the data of this paper gives

$$(J - K)_{\mathrm{2MASS}} = -0.018(0.003) + 0.969(0.004)(J - K) \qquad \sigma = 0.28. \tag{5}$$

Note also that the intercept in the updated Carpenter transformation should be set to zero, since it is not statistically significant.

The *K*-band transformation also differs from that given in Carpenter (2001) (as well as the updated transformations). If the squares of colours are excluded, then the preferred models are

$$K_{\mathrm{2MASS}} = -0.006(0.003) + K - 0.0282(0.027)(J - H) + 0.203(0.022)(J - K) \qquad \sigma = 0.027, \tag{6}$$

or the three-term form

$$K_{\mathrm{2MASS}} = -0.005(0.003) + K - 0.029(0.005)(J - H) \qquad \sigma = 0.029. \tag{7}$$

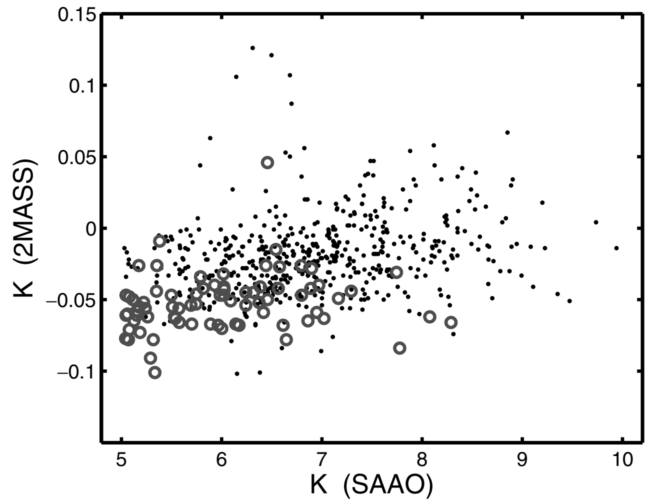

Figure 8. Differences between 2MASS and SAAO K-band photometry from the final sample, plotted against the SAAO K-band photometry. Data for the redder stars [$(J - H) > 0.8$] are plotted as the open circles.

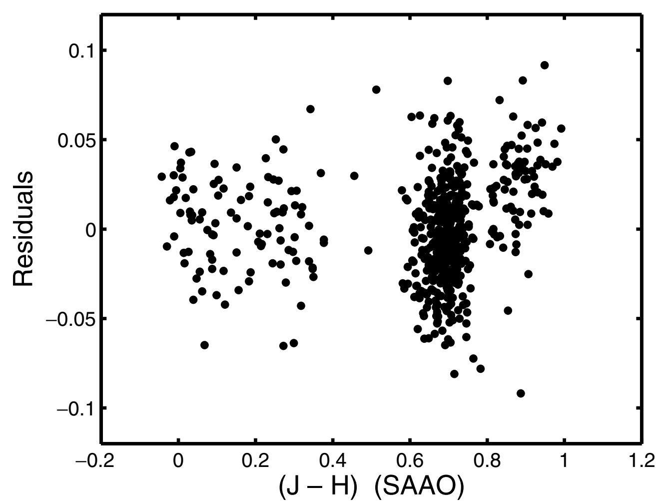

Figure 9. The dependence on $(J - H)$ of the residuals of the simplified $(J - K)$ transformation in equation (5).

The presence of some of non-linear colour terms in the full transformation equations above may have come as a surprise to some readers. Some graphical evidence in support of these therefore follows. The residuals of the K-band transformation

$$K_{2MASS} = -0.023 + K \quad (8)$$

are plotted in Fig. 7: the reason for the term in $(J - H)^2$ in the full transformation equation in (1) is evident. Another view is provided in Fig. 8: this diagram is similar to Fig. 6, but data for the redder [$(J - H) > 0.8$] stars are shown by the open circles. It is clear that at a given colour these stars are, on average, fainter than the bluer population – hence their predominantly negative residuals in Fig. 7.

A further example (Fig. 9) shows the utility of the quadratic term in $(J - H)$ in the $(J - K)$ transformation: the residuals in this case are from (5) above.

A closer look at Figs 7 and 9 suggests that step functions may better describe the behaviour of the residuals than the quadratics used in this paper. Since piece-wise descriptions are perhaps more complicated than warranted by the quality of the data, and since the gain in accuracy would be small, this will not be pursued.

A glance at Fig. 1 shows that the group of stars with $(J - H)_{SAAO} > 0.8$ which give rise to the non-linearities in Figs 7 and 9 are red giants; since these were specifically targeted for observing by us, they are of course much more abundant in the present sample of stars than in that studied by Carpenter (2001).

5 INVERSE TRANSFORMATIONS

Proceeding as above, transformations from the 2MASS to the SAAO system are

$$\begin{aligned}
J_{\mathrm{SAAO}} &= 0.029(0.003) + J + 0.070(0.010)(J - K) - 0.045(0.016)(J - H)^2 \quad \sigma = 0.027,\\
H_{\mathrm{SAAO}} &= H + 0.555(0.126)(H - K)^2 - 0.441(0.050)(H - K)\\
&\quad + 0.089(0.009)(J - H) \quad \sigma = 0.026,\\
K_{\mathrm{SAAO}} &= 0.009(0.004) + K + 0.195(0.023)(J - H)^2\\
&\quad - 0.156(0.023)(J - H) + 0.304(0.079)(H - K) - 0.615(0.183)(H - K)^2 \quad \sigma = 0.027,\\
(J - H)_{\mathrm{SAAO}} &= 0.034(0.004) + 0.398(0.078)(J - H) + 0.541(0.071)(J - K)\\
&\quad - 0.625(0.168)(H - K)^2 \quad \sigma = 0.026,\\
(H - K)_{\mathrm{SAAO}} &= -0.016(0.004) + 0.279(0.016)(J - K)\\
&\quad - 0.234(0.020)(J - H)^2 + 1.104(0.072)(H - K)^2 \quad \sigma = 0.028,\\
(J - K)_{\mathrm{SAAO}} &= 0.018(0.004) + 0.828(0.077)(J - K) - 0.235(0.022)(J - H)^2\\
&\quad + 0.390(0.092)(J - H) + 0.460(0.180)(H - K)^2 \quad \sigma = 0.027. \qquad (9)
\end{aligned}$$

Simplified three- and two-term forms are

$$\begin{aligned}
J_{\mathrm{SAAO}} &= 0.033(0.003) + J + 0.044(0.004)(J - K) \quad \sigma = 0.027,\\
H_{\mathrm{SAAO}} &= -0.004(0.002) + H - 0.209(0.042)(H - K)^2 \quad \sigma = 0.028,\\
K_{\mathrm{SAAO}} &= 0.006(0.003) + K + 0.049(0.007)(J - H)^2 \quad \sigma = 0.027,\\
(J - H)_{\mathrm{SAAO}} &= 0.060(0.003) + 1.036(0.006)(J - H) \quad \sigma = 0.030,\\
(H - K)_{\mathrm{SAAO}} &= -0.012(0.003) + 0.876(0.016)(H - K) \quad \sigma = 0.031,\\
(J - K)_{\mathrm{SAAO}} &= 0.027(0.003) + 1.021(0.004)(J - K) \quad \sigma = 0.029. \qquad (10)
\end{aligned}$$

6 CONCLUSIONS

The transformations between the 2MASS and SAAO photometric systems have been re-examined and extended. There is an excellent agreement between the simplified transformations for $(J - H)$ and $(H - K)$ in equation (3) and the updated Carpenter transformations in equation (4). Transformations of K and $(J - K)$ given here should be preferred.

Finally, we remark on the apparent linear dependence of $K_{\mathrm{2MASS}} - K_{\mathrm{SAAO}}$ on K_{SAAO} in Fig. 6. It is not clear whether this is due to the colour selection criteria of the sample of stars, or to non-linearities in the flux responses of either (or both) sets of photometry. If the coefficient of the K-magnitude is left as a free parameter in the transformations (instead of being fixed at unity), it is found to be very significantly different from 1, despite the presence of several colour terms in the equation. This is suggestive of a non-linearity. A further investigation of this point will be interesting, although probably of little practical importance.

ACKNOWLEDGMENTS

Use of the Simbad data base and the 2MASS point source catalogue is gratefully acknowledged. The authors are grateful to Dr Patricia Whitelock (SAAO) for quality control of the photometry, and for comments on this paper, and also to the referee, Dr Petr Harmanec, for criticism which led to improvements. We hasten to add that we accept the final responsibility for any remaining errors/inaccuracies.

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