A&A 413, 1037–1043 (2004)
DOI: 10.1051/0004-6361:20031576

Astronomy
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Astrophysics

J – *K* DENIS photometry of a VLTI-selected sample of bright southern stars[⋆,⋆⋆]

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Received 8 August 2003 / Accepted 2 October 2003

Abstract. We present a photometric survey of bright southern stars carried out using the DENIS instrument equipped with attenuating filters. The observations were carried out not using the survey mode of DENIS, but with individual target pointings. This project was stimulated by the need to obtain near-infrared photometry of stars to be used in early commissioning observations of the ESO Very Large Telescope Interferometer, and in particular to establish a network of bright calibrator sources.

We stress that near-infrared photometry is peculiarly lacking for many bright stars. These stars are saturated in 2MASS as well as in regular DENIS observations. The only other observations available for bright infrared stars are those of the Two Micron Sky Survey dating from over thirty years ago. These were restricted to declinations above ≈−30°, and thus cover only about half of the sky accessible from the VLTI site.

We note that the final 2MASS data release includes photometry of bright stars, obtained by means of point-spread function fitting. However, this method only achieves about 30% accuracy, which is not sufficient for most applications.

In this work, we present photometry for over 600 stars, each with at least one and up to eight measurements, in the *J* and *K* filters. Typical accuracy is at the level of $0\overset{\mathrm{m}}{.}05$ and $0\overset{\mathrm{m}}{.}04$ in the J and K_{s} bands, respectively.

Key words. surveys – infrared: stars – techniques: photometric

1. Introduction

The recently inaugurated ESO Very Large Telescope Interferometer (VLTI, Glindemann et al. 2003) is one of the most powerful infrared interferometers in the world, and the leading facility in the southern hemisphere. In order to derive meaningful scientific data, interferometric measurements require the calibration of the fringe visibility on sources with a known diameter. Given the long baselines of the VLTI, up to 200 m, such calibrator sources must have diameters known with very good accuracy, and one approach is to make estimations based on theoretical models. This in turn requires that the bolometric flux of these stars be known with good approximation, which calls for good photometry. For various reasons, related to both stellar statistics and to stellar activity, calibrators tend to be chosen primarily among G, K and early M stars, which emit most of their energy in the near-infrared range.

The issue has also another side: in the case of scientific targets, for which the VLTI was intended to derive first-time diameters, it would be impossible to derive astrophysical parameters such as the effective temperature without a detailed knowledge of the bolometric flux.

When the VLTI team began to address the problem of identifying suitable calibrator stars and scientific targets for their initial commissioning observations, it was quickly realized that the amount of photometric data available was not sufficient

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[⋆] Based on observations collected at the European Southern Observatory, La Silla.

[⋆⋆] Tables 1 and 2 are only available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via
`http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/413/1037`

for most stars. In this early mode of operation, the VLTI used mostly two small siderostats (Paresce et al. 2002), which effectively limited the sensitivity to bright objects ($K \lesssim 3$ mag).

The available near-infrared photometry for such stars in the southern hemisphere is very scarce. On one side, modern photometric surveys such as DENIS (Epchtein et al. 1997) and 2MASS (Cutri et al. 2000) are typically saturated on bright stars. The overexposure limit of DENIS is about $6\overset{\mathrm{m}}{.}5$ in K_{s} and about $8\overset{\mathrm{m}}{.}0$ in J. 2MASS has slightly lower overexposure limits using a very short pre-exposure of 53 millisec. But those short exposures somewhat suffer from the fact of the undersampled point spread function (PSF) of the individual speckles. On the other side, the Two Micron Sky Survey (TMSS, Neugebauer & Leighton 1969), carried out about thirty years ago, has much higher saturation limits but was limited to declinations above $\approx -30°$. It also suffers from a limit to sources brighter than $2\overset{\mathrm{m}}{.}5$ in K and it contains no J band. Individual measurements of some targets exist. But none of those data sets is homogeneous with respect to filter set, calibration and time coverage.

We were using the DENIS survey instrument, adding attenuating filters. The attenuation factor is about 120 ($\approx 5\overset{\mathrm{m}}{.}2$). This project, although using an existing survey instrument, is completely independent from the point of view of data taking strategy, calibration and data handling. The data does not go through the normal survey data pipeline. We present the methods and the calibration, used to derive an accurate and homogeneous catalogue of NIR photometries. The project, presented here with its primary photometric results, also covered variable stars like AGBs, Miras and Cepheids. All this was done as close as possible to the epoch of the observations of the commissioning instrument (VINCI) of the ESO VLTI.

2. The sample

The sample was selected by two of us (namely I.P. and A.R.) on basis of their lists for the interferometric catalogues and surveys (CHARM, Richichi & Percheron 2002). The selection criterium was first of all to obtain a spatially uniform network of calibrators (Fig. 1). Additionally the region of the galactic plane was covered, adding numerous sources of different spectral type and intensity (Fig. 2). Due to the stop of the DENIS project early in September 2001, the targets between 0^{h} and 6^{h} unfortunately had to be skipped.

We searched the SIMBAD data base for known spectral classifications (Fig. 3). Although this information is somewhat biased due to the inhomogeneous data resources, we find our sample is well distributed from B to M stars with some peak at K. The (J–K_{s}) distribution of those stars without spectral classifications (Fig. 4) suggests that most of the unclassified targets fill up at late spectral types. But also stars with circumstellar shells and giants with strong interstellar reddening are contained in this section.

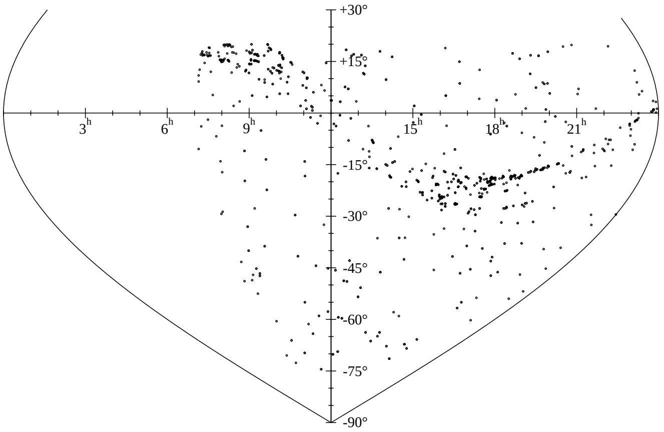

Fig. 1. The spatial distribution of the targets. The northern limit of $\delta = +20°$ by far exceeds that of the DENIS sky survey ($\delta = +2°$). Although the galactic plane is somewhat pronounced, there is a uniform distribution, which makes the sample well suitable as calibrators. Due to the limited observational period, we were unable to cover the range 0^{h}... 6^{h}.

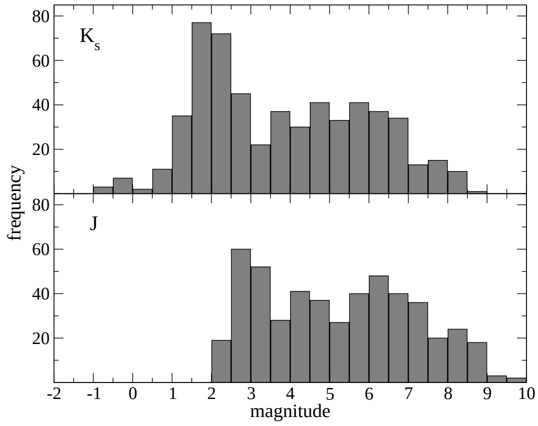

Fig. 2. The magnitude distribution of the stars in the final catalogue. Only a few stars above the magnitude limits ($K_{\mathrm{s}} \approx 0\overset{\mathrm{m}}{.}5$, $J \approx 2\overset{\mathrm{m}}{.}5$) were observed and calibrated by fitting the PSF.

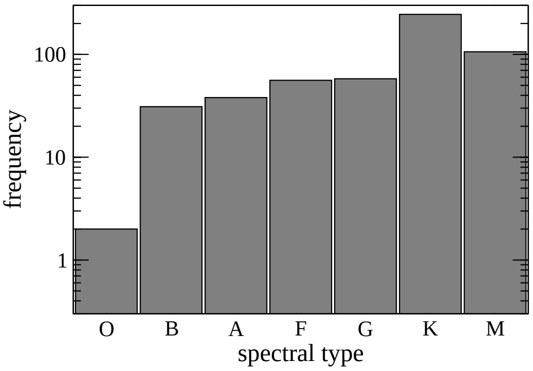

Fig. 3. Distribution of spectral types for those sample stars having an MK classification in the SIMBAD data base.

3. Observations and data reduction

The observations were performed with the ESO 1 m telescope at La Silla, Chile, which was fully dedicated to the DENIS project from 1994 to September 2001. The frames were taken in 22 nights from April to September 2001. A very limited set of about 50 standard stars and about 10 targets were taken during the feasibility study in February 2001. In total 608 targets were in the input lists. For 6 targets no reliable detection was

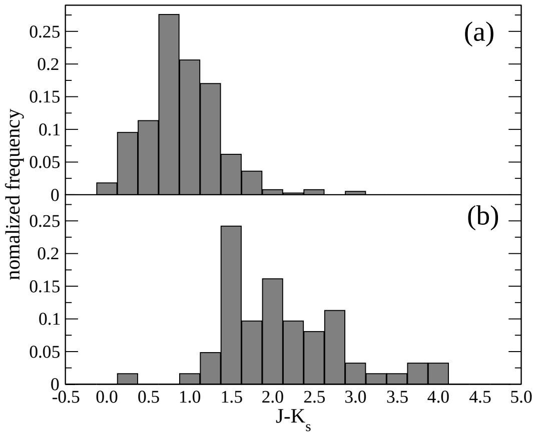

Fig. 4. The normalized frequency distribution of (J–K_s) for those stars with a spectral classification **a)** and without **b)**. Most of the sources without spectral classification have to be of late type.

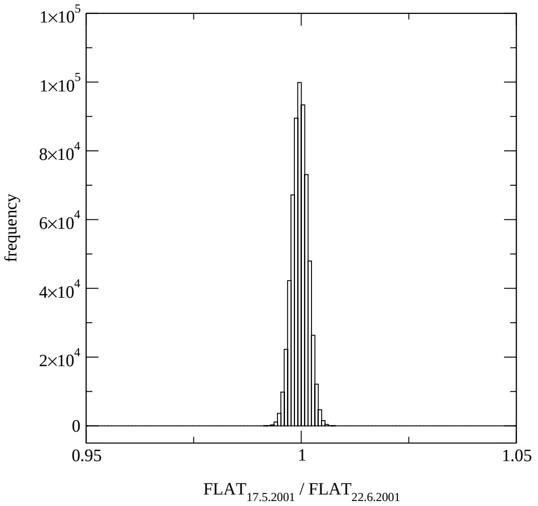

Fig. 5. The frequency distribution of the flatfield variation of two consecutive nights.

possible. Either the targets are too faint to be detected with the attenuator or the input coordinates from very old IR identifications were too inaccurate. Thus the final catalogue contains 602 objects with at least one measurement (one measurement comprises 4 to 5 frames – see below). A large fraction of the targets has been visited several times (up to 8). This repetition was usually not in the same night and, in any case, at least more than one hour apart. In total 14 270 target frames during 1780 individual pointings were used for the final catalogue.

The attenuation was obtained using normal filters covered with a thin reflecting surface. The Gunn-I band camera had no such equipment. Therefore this catalogue here covers only the near infrared bands J and K_s.

Five frames, 10 s exposure time each, are taken for every target at every pointing. A telescope offset of 100″ moves the target over the chip. This provides information for the flatfield stability and the internal error. It also results in sufficient amount of backup to repair for defects in the NICMOS arrays. It allows a first test for the reliability of the measurement. In a few percent of all data sets one out of the five K_s frames had to be removed. For 0.1% of the pointings more than one frame was affected. These measurements were not used for the catalogue. In J band the chip had more defects and thus observations with only three usable frames were taken into account too.

The complete reduction described below is implemented in a fully automated pipeline at a Linux based system at the Institute of Astrophysics at the University of Innsbruck. The reduction of a whole night needed about 2 hours of CPU time and about 1.5 hours of tape I/O. Sources with well known coordinates were used to derive a pointing model for the night. Thereafter the remaining sources were searched on the frames on basis of the published coordinates. As there are normally no other visible sources on a single frame, no astrometry can be achieved. Thus in a very few cases possible contamination of the catalogue object by a very bright nearby source may occur.

3.1. The flatfield

As the sky is, even in twilight, too faint to obtain well exposed frames with the attenuators, a set of about 50 non attenuated frames were taken every night. Those frames are cleaned from sources by median filtering of the individual pixels from multiple frames. The sky background results, after normalization, in a perfect flatfield. The variations of the flatfield intensity of the inner part of the array (10 percent boundary removed as not used for the target observations) do not exceed 20 percent. The majority of the pixels lies within ±10 percent. Thus the flatfield correction does not affect the statistical noise properties of the observations at individual positions.

Figure 5 gives the frequency distribution of the values of the quotient of two such flats obtained in different nights. It is a perfect Gaussian with a FWHM of less than one percent. This is about double the error expected from pure photon statistics of the individual flat images. The origin of this increase is expected to be caused by moving (defocused) dust features on the optical elements of the instrument.

Although we get a stable flatfield for the whole optical system and the detector array in this way, it does not include small thickness variations of the reflecting surface, which is used as attenuator. Therefore the deviation of the individual frames from the mean values are plotted as function of the position for all sources (for discussion of the source extraction see Sect. 3.2).

We find a variation of up to 5 percent in flux as function of the position on the frame for the K_s filter. This pattern was absolutely stable throughout all frames and all the observational nights. Figure 6 shows that the deviations from the mean values as function of the position on the frame. We obtain nearly Gaussian error distributions centered at different points for each of the 5 individual positions. It gives us the internal accuracy of about two percent (after flatfield). The centers of those distributions were used to correct the error in the original flatfields. This results in an internal noise, which is of the same

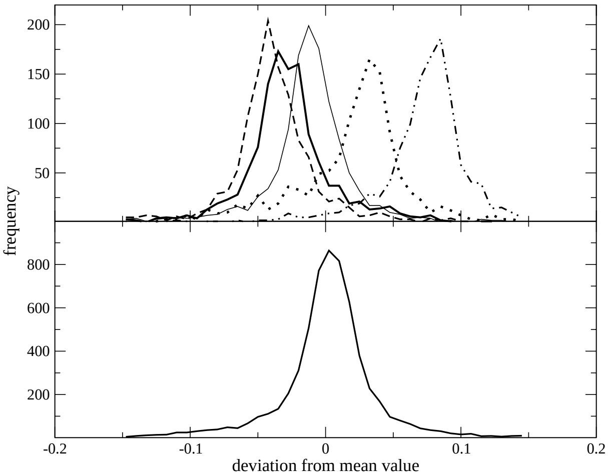

Fig. 6. The upper panel shows the variation of the individual measurements for each of the 5 position subsets in $K_{\rm s}$. The zero point offset between the measurements represent the local changes of the attenuation factor of the grey filter surface. The lower panel shows the sources after correction. The J filter does not show this effect.

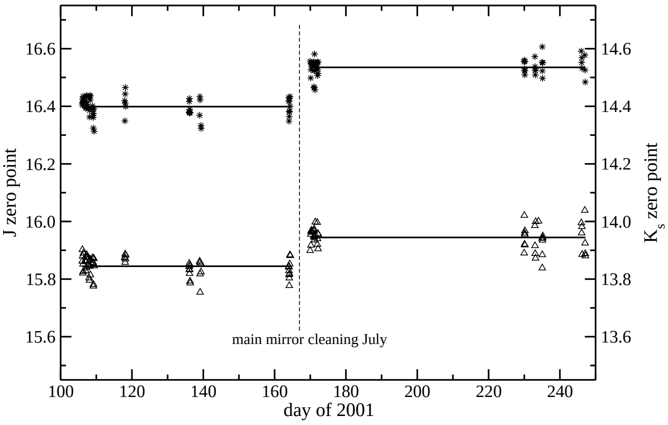

Fig. 7. The instrumental zero points derived from the individual standard measurements during the whole survey. The cleaning of the telescope main mirror gave the only major change of this parameter.

order of magnitude as that of the individual subset. The J filter does not show such an effect.

3.2. Source extraction

For source extraction SExtractor v2.1.6 (Bertin & Arnouts 1996) was used. The parameters used for setup are 3×3 pixels Gaussian filtering (=default setup) and fixed aperture photometry with $10''$ (for a discussion of the radius see Fouque et al. 2000). The typical FWHM of the sources on the frames is just above $3''$. As the sources are bright and the attenuator clips faint background sources, crowding never was a problem. Tests without any filter gave the same results for more than 98% of the sources. The remaining sources have a slightly higher rms between the 5 individual frames. We attribute this to glitches and cosmic ray events on individual frames, properly removed by the filter.

The overexposure limits for our setup are $K_{\rm s} \approx 0\overset{\rm m}{.}5$ and $J \approx 2\overset{\rm m}{.}5$. A few stars brighter than that were observed and calibrated by fitting the PSF.

3.3. Photometric calibration

From the total set of standards used for the DENIS survey a subset of fourteen bright stars, well distributed in right ascension, were selected. The DENIS standards were the fainter stars from Carter (1990) combined with some "private" lists from SAAO (see Fouque et al. 2000). Additionally five very bright standards were picked from the list of Carter now here. Typically ten of them were observed in each night in about 25 to 30 individual measurements, containing 5 frames at the same positions on the arrays like targets stars. Those observations were taken in blocks of 4 to 5 standards once every hour. Thus we follow an individual star over a large range of airmass from 1 to 2.5. This is a large extension, compared to the calibration done in a DENIS survey night. Even with this set, we are unable to derive every night independently, numerically stable, all parameters of the nonlinear extinction in the NIR (Manduca & Bell 1979). As the physical zero point of the instrument changes only very slowly on timescales of months or even years, and as the nonlinear extension (Manduca & Bell 1979) also has only low frequency seasonal dependencies, those parameters are fixed on long time scales. This allows us a stable determination of the extinction on a night to night basis. This is also in discrepancy to the calibrations of the DENIS and the 2MASS survey, where a fixed extinction was used applying a variation of the zero point (see e.g. Cioni et al. 2000).

The 2MASS consortium adds in the J band a time dependent correction making up to $0\overset{\rm m}{.}1$ during a night (Cutri et al. 2000). This allows to correct for high frequency variations of the atmospheric transmission, as known in the J band due to non saturated molecular bands. In our calibration data set this additional freedom seems to us not well enough defined. Thus it was not included into the automated pipeline. These variations cause the absolute error in J to be higher than in that $K_{\rm s}$.

The main mirror of the telescope was cleaned in mid-July 2001. Only this gave a significant change of the instrumental zero point during the project.

The extinction varied within the survey significantly. Nights with high or unstable extinction in at least one band were excluded in both bands.

3.4. Error estimates

At several levels within the pipeline we are able to obtain error information. The five individual frames (having 10 s exposure time) are taken during a sequence lasting 100 s, and thus are already sensitive to high frequency variations caused e.g. by cirrus clouds. This kind of test may be used not only for standards, taken every hour in a single block of about 10 min, but also for all target observations. The information on this rms σ between the individual frames of one pointing for the final catalogue observations are plotted in Fig. 8. The values of this internal variation σ are typically below $0\overset{\rm m}{.}03$ and thus the internal error of the mean is below $0\overset{\rm m}{.}012$.

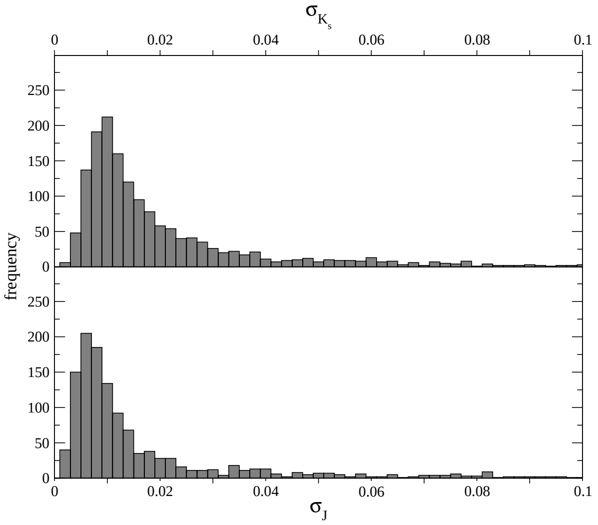

Fig. 8. The frequency distribution of the variations of the individual detections on each 10 s exposure during one pointing (100 s).

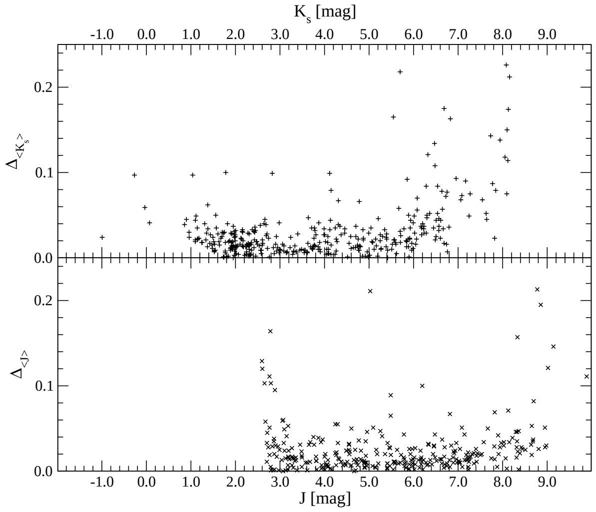

Fig. 9. The deviations of the repeated target observations. Clearly visible is the dependency of the absolute errors near the overexposure limit and at the faint end of the observations. The figure is not cleaned from possible variable targets. Thus the errors given here are upper boundaries.

The standards, as repeated individually, and the derived extinction, are giving the next step of information. As the zero point is fixed, the residuals depend on the airmass, if the transparency of the sky changes. Combining all nights the noise on the standards is about $0\overset{\mathrm{m}}{.}05$ in K_s and $0\overset{\mathrm{m}}{.}08$ in J. The slightly higher error in J is caused by minor weather variations and thus variations of the atmospheric bands at the borders of the filter range. There is no indication of an airmass dependency over the whole range.

As already mentioned above, most of the targets were reobserved in different nights. The variation Δ of those observations (Fig. 9) is also a good indicator for the total accuracy. It shows a typical deviations in the same order of magnitudes like those of the standard stars. It also redetermines the boundaries for over– and underexposure limits mentioned above. During nights where several sources, observed consecutively, show high variations, all sources within $\pm 0\overset{\mathrm{h}}{.}5$ were removed from the final lists. This occurred in two nights where the criteria above have not removed the data already.

We defined a variability probability combining the internal error and the variation of repeated observations by

$$\begin{aligned}
\mathrm{var}_J &= f \qquad \forall f_J > 0 \qquad f_J := \mathrm{int}\left(\frac{\Delta_J}{\sigma_J} - 1\right)\\
\mathrm{var}_J &= 0 \qquad \mathrm{else}\\
\mathrm{var}_K &= f \qquad \forall f_K > 0 \qquad f_K := \mathrm{int}\left(\frac{\Delta_K}{\sigma_K} - 1\right)\\
\mathrm{var}_K &= 0 \qquad \mathrm{else}\\
\mathrm{var} &= \max(\mathrm{var}_J, \mathrm{var}_K).
\end{aligned}$$

This number is given in the final catalogue.

4. The catalogue

The final catalogue contains 602 targets. 36 sources do not have K_s band magnitudes as there was no reliable detection or even sometimes the files were corrupted on the tapes. 135 sources are missing J values.

The first table of the catalogue contains the mean values and the cross-referencing to the IRAS and the TMSS catalogue. The columns of Table 1 are:

1. sequence number ($N = 1\ldots602$).
2. usual name.
3. right ascension (J2000.0) from SIMBAD.
4. declination (J2000.0) from SIMBAD.
5. IRAS identifer (if available).
6. IRC identifer (if available).
7. number count n of pointings.
8. mean JD (−2 400 000) of all pointings.
9. mean K_s magnitude.
10. number count of K_s measurements.
11. error of mean K_s value.
12. mean J magnitude.
13. number count of J measurements.
14. error of mean J value.
15. variability probability (see above).
16. IRC K magnitude (if available).
17. spectral type from SIMBAD (if available).
18. remarks.

The second table of the catalogue contains the information about all individual pointings. The columns of Table 2 are (Cols. 4–10 repeated up to 8 times):

1. sequence number N from Table 1.
2. usual name.
3. number of pointings (same as in Table 1).
4. JD (−2 400 000) of the individual pointing.
5. K_s magnitude.
6. rms of K_s value.
7. number count of K_s frames used.
8. J magnitude.
9. rms of J value.
10. number count of J frames used.

Table 1. Sample table of the main catalogue. The full table is available in electronic form at the CDS.

Nr	Name	α(J2000)	δ(J2000)	IRAS	IRC	n	<JD>	<K>	n_K	Δ_K	<J>	n_J	Δ_J	var	$K_{\rm IRC}$	type	remark
	....																
171	HD 96274	11 06 02.2399	+01 12 38.391	11034+0128	+00202	5	52026.02	2.454	4	0.002	3.488	4	0.018	0	2.33	M	
172	SAO 99437	11 06 13.365	+10 18 29.64			5	52026.03	7.941	4	0.138	8.222	5	0.039	0		F8	
173	HD 96374	11 06 37.272	+09 57 30.93			5	52026.03	7.167	4	0.090	7.401	5	0.026	0		F8	
174	HD 96479	11 07 13.2751	+10 12 44.038			5	52026.03	6.233	4	0.037	6.459	5	0.030	0		F5 IV	
175	SAO 99456	11 07 22.875	+10 11 43.38			5	52026.04	6.032	1	0.047	8.252	5	0.471	4		F8	
176	HD 96918	11 08 35.3899	-58 58 30.133	11064-5842		5	52026.62	1.557	5	0.050				0		G0 I	Cepheid
177	HD 97576	11 13 14.6854	-44 22 19.978	11109-4405		4	52028.38	1.783	4	0.100	2.784	3	0.164	1		K7 III	
178	HD 97716	11 14 37.7223	-01 16 14.965	11120-0059		5	52026.62	4.077	4	0.005	4.727	5	0.014	0		K0	
179	HD 98118	11 17 17.4003	+02 00 38.001	11147+0217	+00203	4	52027.63	1.337	4	0.021	2.203	1	0.041	0	1.40	M0 III	
	....																

Table 2. Sample table of the catalogue of the individual measurements. Columns 4–10 are repeated up to 8 times for each of the n pointings. The full table is available in electronic form at the CDS.

Nr	Name	n	JD	K	σ_K	i_K	J	σ_J	i_J	...
	....									
171	HD 96274	5	52046.591	2.453	0.022	5	3.530	0.003	4	...
172	SAO 99437	5	52016.645	7.638	0.080	5	8.228	0.094	4	...
173	HD 96374	5	52046.593	7.031	0.030	4	7.453	0.028	4	...
174	HD 96479	5	52046.595	6.205	0.023	4	6.468	0.012	4	...
175	SAO 99456	5	52016.648	6.032	0.047	5	6.467	0.011	5	...
176	HD 96918	5	52016.626	1.661	0.020	5				...
177	HD 97576	4	52016.627	1.677	0.027	4	2.684	0.004	3	...
178	HD 97716	5	52016.639	4.076	0.020	4	4.770	0.011	3	...
179	HD 98118	4	52046.597	1.349	0.056	5				...
	....									

5. Results

The catalogue presented here gives for the first time accurate NIR photometries for a large set of bright stars in the southern sky. We have shown that the relative and the absolute accuracy is resulting in errors of less than 4% in $K_{\rm s}$ and less than 6% in J typically. The 2MASS survey in its final release provides PSF fitted values for overexposed sources. Cutri et al. (2000) note typical errors of 30 to 40% for those sources. We compared our results with their photometry in Fig. 10.

The northern part of our survey overlaps with the southern part of the TMSS survey (K band only). 196 stars are common with our data set. The comparison, together with that of the 2MASS survey, is shown in Fig. 11.

All IRC/TMSS sources are in the domain of overexposed 2MASS sources, which is pronounced by the higher scatter. The typical error of an IRC source is given with $0\overset{\mathrm{m}}{.}1$, which can be seen well in the comparison with our photometry. The systematic shift is due to the color equation. While Neugebauer & Leighton (1969) used a classical K filter, 2MASS and DENIS are using $K_{\rm s}$. In the comparison with the 2MASS this effect is smeared out due to the lower accuracy.

Acknowledgements. The DENIS project is partly funded by the European Commission through *SCIENCE* and *Human Capital and Mobility* plans under grants CT920791 and CT940627. It is

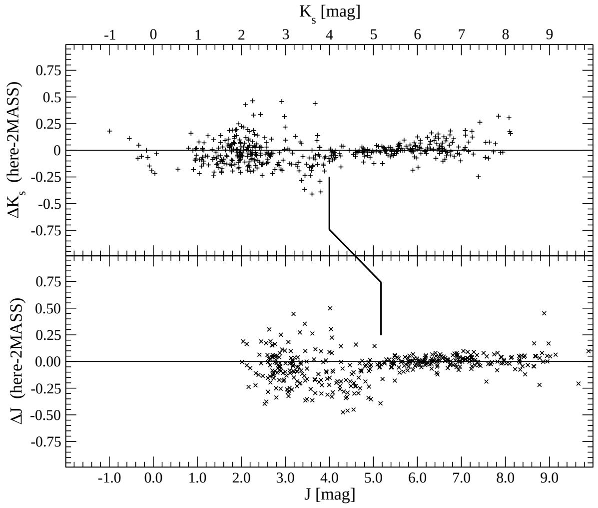

Fig. 10. The comparison of our photometry (sources with var $<$ 3) with 2MASS (final release). The line marks the overexposure limits of 2MASS. These values are well pronounced by the increasing scatter. At the faint end the scatter originates from the limits of our photometry.

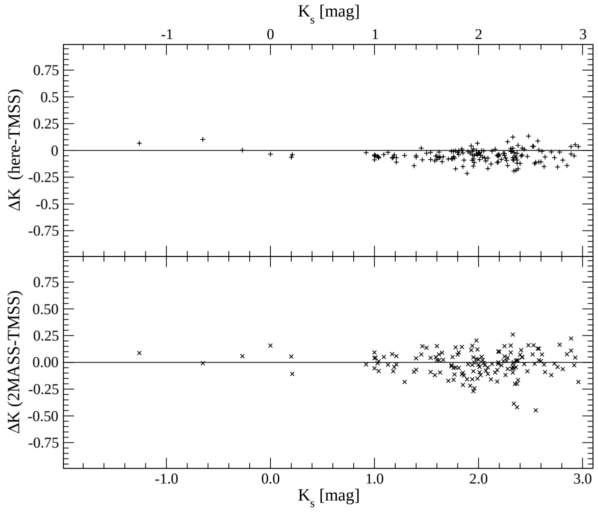

Fig. 11. Comparing TMSS survey targets in our sample to our photometry (upper panel) and to the 2MASS photometry (lower panel). The different accuracies are clearly visible.

supported in France by INSU, MEN and CNRS, in Germany by the State of Baden-Württemberg, in Spain by DGICYT, in Italy by CNR, in Austria by the *Fonds zur Förderung der wissenschaftlichen Forschung* and the *Bundesministerium für Bildung, Wissenschaft und Kultur*, in Brazil by FAPESP, in Hungary by OTKA grants F-4239 and F-013990, and by the ESO C&EE grant A-04-046.

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