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POSITIONAL AND THEORETICAL ASTRONOMY

Astrometric Catalogue of Stars in the Equatorial Zone KMAC2

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Abstract—A catalogue of positions and V magnitudes of stars down to 17^m in the declination zone from 0 to +2° is compiled. The catalogue contains 1.09×10^6 stars and is based on observations obtained at the meridian axial circle of the Main Astronomical Observatory, National Academy of Sciences of Ukraine and Astronomical Observatory of Kyiv National University in 2001–2005. The accuracy of positions and photometry is 0.05–0.07″ and $0.05–0.08^m$, respectively, for stars of $11–14^m$.

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INTRODUCTION

In 1986, the meridian axial circle (MAC), a tool with a horizontal tube and an entry hole of 180 mm, was developed at the Main Astronomical Observatory of the National Academy of Sciences of Ukraine and the Astronomical Observatory of Kyiv National University. In 2000, a CCD-camera based on the ISD017AP matrix with a resolution of 1040 × 1160 pixels was mounted on the MAC. From 2001 to 2003, it was used to observe stars in areas with radiosources, ICRF objects. The KMAC1 catalogue was obtained. It contains 115 032 stars in 192 fields [6, 10]. The catalogue is stored in the CDS database at http://cdsarc.u-strasbg.fr/viz-bin/Cat?J/A+A/438/377. By comparison with catalogues UCAC2 and CM13, it was found that positioning errors are within ±0.04–0.07″ for stars of $V < 14^m$ and errors of V values were $\pm 0.05–0.07^m$. The MAC photometry recreates the V photometric band of the Johnson standard system.

In 2001, thanks to quite good astrometric characteristics of the MAC, a long-term program of observations of stars in the equatorial zone was initiated in order to extend the reference system HIPPARCOS–Tycho on the stars down to $V = 17^m$ and to obtain their photometric characteristics. Under this program, by 2005, images of 90% of the sky in the declination zone from 0 to +2° were obtained with nearly 5×10^6 photocenters of starlike objects. In 2005, the camera stopped working. Therefore, since 2010 observations have been continued with a new CCD camera: Apogee Alta U47 [1]. Below, the processing of observations conducted in 2001–2005 and the compilation of the catalogue KMAC2 (Kyiv Meridian Axial Circle Catalogue no. 2) are described. It is planned to store it in the catalogue database at http://cdsarc.u-strasbg.fr/viz-bin.

OBSERVATIONS AND THEIR PROCESSING

Observations

Observations were carried out in the time delayed integration (TDI) mode, which is normally used in observations on meridian circles with CCD cameras [3, 8, 9, 11]. When the telescope was positioned on the meridian in this mode, images of the sky are recorded with a fixed size of 24.2′ in declination and of any size in right ascension, in the direction in which images of stars move on the matrix with the daily motion speed because of the TDI. Thus, a fixed telescope scans the sky, and a typical image obtained as a result of a scanning session of 0.5–5 hours contains an image of the sky in the form of a strip with the size of 24.2′ in declination (coordinate axis x in the image) and 5–100° in right ascension (the axis y). In total, 386 scanned images of different parts of the sky of different sizes evenly spaced in the observation area were obtained for 2001–2005. For approximately 30% of the parts of the sky, only single images were obtained.

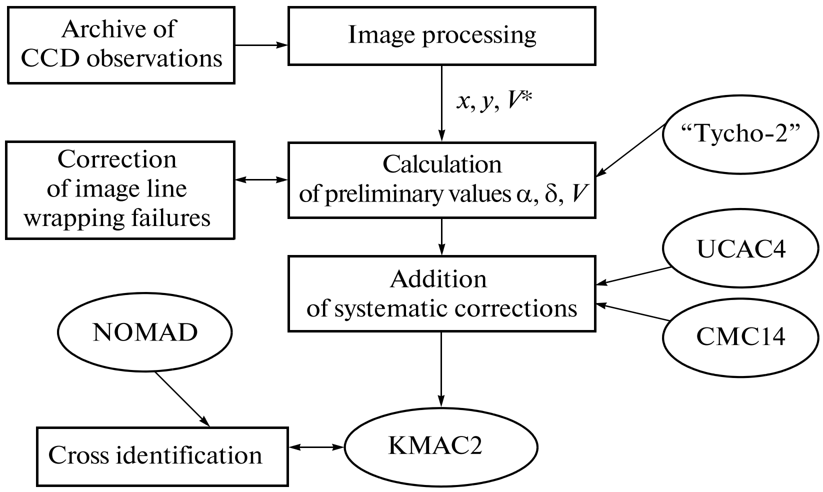

Fig. 1. Catalogue KMAC2 compilation procedure: the main stages of reduction and catalogue comparison.

General Observation Processing Scheme

When processing, the method that was used in the compilation of the KMAC1 catalogue was used only partially because of the significant difference in the positions of scanned areas in the sky. The processing method used in [6] is suitable only in the case when boundaries of scanned areas of the sky completely coincide in repeated observations. This condition is no longer satisfied. Furthermore, since accurate V values obtained within the program APASS [7] could be used, the MAC photometry systematic error was calibrated directly according to these data.

The main catalogue compilation stages are shown schematically in Fig. 1 and include the calibration of files with images of the sky, star photocenters' selection, calculation of their CCD coordinates and magnitudes, identification of reference stars of Tycho-2, calculation of equatorial coordinates, identification of catalogue systematic errors by the comparison with other more accurate catalogues, and exclusion of these errors. Because of the identified defects of the wrapping of CCD camera image lines, we used an additional iteration loop in order to correct these defects, adjust measured coordinates y, and recalculate equatorial coordinates. Given that only single images were obtained for 30% of parts of the sky, the filter of nonstar images with a single measurement of the photocenter by the cross-identification of KMAC2 with NOMAD was added to the standard scheme of observation processing.

Image Calibration and Determination of Star Photocenters

The image calibration was based on the method used in the compilation of the catalogue KMAC1 [6]. It consisted in the exclusion of changes in the average level of the background by coordinates x and y. It was achieved by monitoring large-scale changes in the background level in both coordinates, their linear interpolation, and then exclusion as the additive intensity component. The heterogeneity of the background level for the individual matrix rows was also eliminated.

However, some image defects could not be eliminated by calibration. This is partly because of the spontaneous emergence or disappearance of cluster of pixels with abnormally high levels of noise on the matrix, which was recorded as fake star centroids. In addition, there were failures in the transfer of rows of the CCD matrix, which led to the disappearance of one or two lines in the image, i.e., to discrete discontinuities of the scale of the coordinates y (in the right ascension increase direction) by 1 pixel = 1.39″ or 2 pixels = 2.78″. These matrix row transfer failures were not accompanied by image distortions. Thus, their detection and correction were performed at later processing steps.

The resulting images of stars have profiles symmetrical by the coordinate y (right ascensions). However, there is some asymmetry along the axis of x. The asymmetry degree depends on the star position on the axis of x and its brightness. In the subsequent processing, it was recorded as a declination systematic error depending on x and magnitude. In addition, the use of the 12-bit analog-to-digital converter did not make it possible to obtain images of stars brighter than $V \sim 11\ldots12^m$ without the saturation of central pixels, which, as will be shown below, led to systematic errors in the photometry and declinations of these stars.

In order to detect the stars in the sky image, pixel intensity readings were smoothed by the 3×3 filter, and the value of the excess of the averaged reference reading over the background by $1.1\sigma'$ was taken as a criterion for the presence of the star, where σ' is the root mean square value of the fluctuations in the background in the nonsmoothed image. Such a relatively low detection level was selected in order to increase the probability of registration of extremely faint stars of $16\ldots17^m$. However, in this case, some background fluctuations were mistakenly recorded as fictitious stars. The number of stars increased sharply with the increase of V and exceeded approximately twice the number of actual stars in the range $V = 16\ldots17^m$.

The position of photocenters x and y of identified stars and their intensities V^* were calculated by the two-dimensional approximation of pixel readings by the Gaussian profile. In the case of the discrepancy of iterative calculations (usually in the case of the deviation of the profile form from the star-shaped one), the method of weighted center of mass was used [5]. Saturated pixels were taken into account with zero weight.

Reduction to the ICRF

For ease of processing, scanned parts of the sky were broken into smaller ones, so that each of them contained 30 to 40 stars of the Tycho-2 reference catalogue [4]. After the identification with this catalogue, measured coordinates of photocenters x and y were compared with tangential coordinates ξ and η of reference stars calculated according to connection formulas [8, 9]:

$$\xi = (\alpha_T - \alpha_0)\cos\delta_0, \quad \eta = \tan(\delta_T - \delta_0), \tag{1}$$

which correspond to the TDI mode of observations near the equator. Here, α_T and δ_T refer to the position of the star according to the Tycho-2 catalogue, and α_0 and δ_0 are the coordinates of the center of the scanned area of the sky. The following model of coordinate transformations was used:

$$\begin{aligned} \xi &= y + A_0 + A_1 y + \ldots + A_n y^n + Bx, \\ \eta &= x + C_0 + C_1 y + \ldots + C_n y^n + Dx \end{aligned} \tag{2}$$

with the approximation of zero-point oscillations of coordinates in time (y-coordinate corresponds to the time) by the order polynomial n. Terms of the type $x^n y^n$ were not included in the model as unimportant. The best results with minimal residuals of differences $y - \xi$ and $x - \eta$ were obtained at $n = 6$. Coordinates ξ and η of measured photocenters of all the stars were calculated with ratios A, B, C, and D of reduction model (2) and subsequently converted in α and δ by the formulas inverse to (1).

The reduction of the measured photometric values V^* to the system of values V_T of the Tycho-2 catalogue is made by the linear approximation

$$V_T = V^* + E_0 + E_1 y, \tag{3}$$

where the term E_1 takes into account changes in the transparency of the atmosphere over time. As is known, the system of photometric values of Tycho-2 differs from the Johnson system. The inconsistency of these systems reaches 0.2^m [2]. Therefore, at the final stage of reductions, V values of MAC obtained in the Tycho-2 system were reduced to the standard system by the comparison with the catalogue UCAC4.

Defects of Image Lines Wrapping

In many cases, the comparison of α for the same stars calculated by observations on different nights i and j revealed the presence of singular points at which the monotonic variation of differences $\Delta\alpha$ with time suddenly discontinues, in differences $\Delta\alpha = \alpha_i - \alpha_j$ of right ascensions in addition to the noise component. There are also local extremes of opposite signs at discontinuity points.

Figure 2a shows the variation of $\Delta\alpha$ with α (i.e., with time) for observations of the part of the sky with the partial overlap in declination conducted on September 7, 2003, and September 18, 2004. For the best selection of graph features, differences $\Delta\alpha$ for the faintest stars are not presented. Seven discontinuities of the variation of $\Delta\alpha$ with discrete amplitudes (local maximum–local minimum) of approximately $1.4''$ and $2.8''$ can be observed, i.e., 1 and 2 pixels in the matrix scale. The discreteness of the discontinuity amplitude indicates that this effect is caused by the loss of lines of pixels in the image of the sky because of the failure of electronics (the horizontal readout register of the CCD matrix) during the transferring of charges in the sky scanning direction, i.e., in right ascension. In order to test this assumption, the graph of differences Δy of coordinates of photocenters for analyzed scans was plotted (Fig. 2b), which revealed an abrupt change in the differences Δy by the value of 1–2 pixels at the same times. Clearly, the change of Δy to a negative value corresponds to a loss of pixel lines in the first of the two compared images, and the change

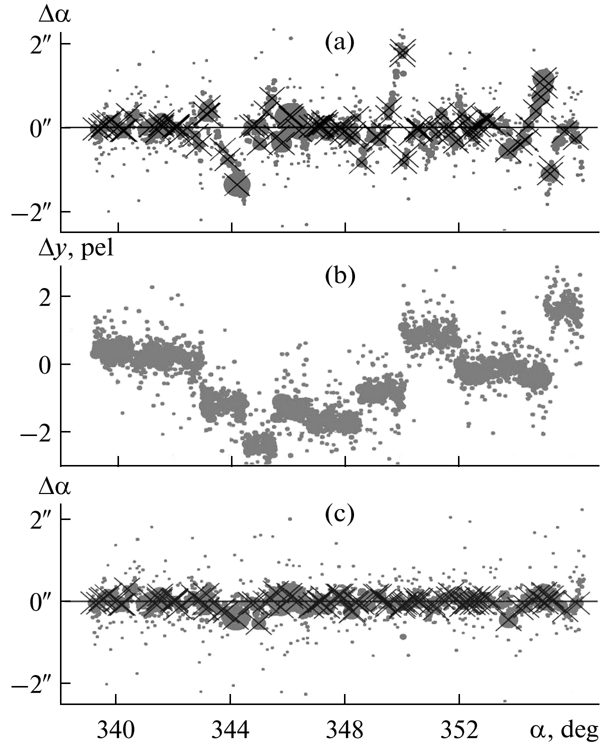

Fig. 2. (a) Differences $\Delta\alpha$ of right ascensions of stars, (b) differences between Δy of coordinates of photocenters between the two images of the same part of the sky, and (c) differences $\Delta\alpha$ after entering corrections for the loss of pixel lines. The size of the circles is proportional to the brightness of stars. Crosses indicate reference stars of Tycho-2

in the positive direction corresponds to the pixel loss in the second image. Differences in declinations are free from such system behavior.

In order to find these image defects, all the possible combinations of pairs of scanned parts of the sky i and j were formed, discontinuities in the systematic change of differences Δy were found, and appropriate corrections of coordinates y of photocenters of star images were made. After the second reduction to ICRF, new calculated differences $\Delta\alpha$, as shown in Fig. 2c, are free from discontinuities.

Preliminary positions and V magnitudes of the KMAC2 catalogue were obtained by averaging of individual star positions obtained on different nights. Formal mean square errors of the position of the photocenter $\sigma_1(\alpha)$, $\sigma_1(\delta)$, and magnitude $\sigma_1(V)$ for each interval V were found from the scattering of these values (table). The average number of measured positions of photocenters for one star in the catalogue is $n = 2.8$. The table also shows the formal errors of the catalogue position $\sigma_n = \sigma_1/\sqrt{n}$ at $n = 2.8$.

Position error of the photocenter σ_1, the average number of measurements n, and the mean error of catalogue positions and photometry σn

V	$\sigma_1(\alpha)$	$\sigma_1(\delta)$	$\sigma_1(V)$	n	$\sigma_n(\alpha)$	$\sigma_n(\delta)$	$\sigma_n(V)$
9^m	0.099″	0.164″	0.246	1.15	0.092	0.153	0.229
10	0.097	0.113	0.146	2.78	0.058	0.068	0.088
11	0.091	0.099	0.094	2.77	0.055	0.060	0.056
12	0.104	0.113	0.103	2.81	0.062	0.067	0.061
13	0.119	0.128	0.112	2.91	0.070	0.075	0.066
14	0.145	0.165	0.133	2.96	0.084	0.096	0.077
15	0.231	0.256	0.185	3.04	0.132	0.147	0.106
16	0.537	0.563	0.317	2.74	0.325	0.340	0.192
17	0.819	0.838	0.314	1.73	0.623	0.638	0.239

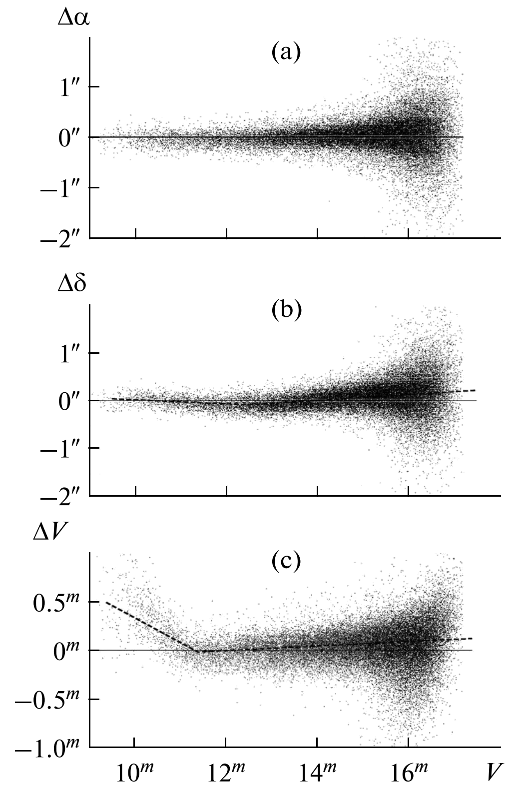

Fig. 3. Systematic differences between KMAC2–UCAC4 in right ascensions, declinations, and V values.

Thus, for stars of $10–15^m$, the mean error in the catalogue position $\sigma_n(\alpha)$, $\sigma_n(\delta)$ is within 0.05–0.1″, and the photometry error $\sigma_n(V)$ lies within $0.05–0.1^m$.

KMAC2 CATALOGUE AND ITS FEATURES

Comparison with UCAC4 and CMC14

In order to identify systematic errors that depend on the magnitude and to independently evaluate of errors of the catalogue, positions of stars and their magnitudes of the previous version of the catalogue KMAC2 were compared with UCAC4 [12] and CMC14 [3]. Differences between coordinates $\Delta\alpha$, $\Delta\delta$, and magnitudes ΔV were formed. The comparison (Fig. 3) showed that there was no systematic dependence of differences $\Delta\alpha$ on V, but there was a dependence of differences $\Delta\delta$ on V. The dotted line shows a function that approximates this systematic dependence with the inflection point in the graph at approximately $V = 12.5^m$. A similar relationship was found for differences ΔV with an inflection point near $V = 11.4^m$. These features are caused by two effects: the saturation of the image with bright $9\ldots13^m$ stars in the CCD camera of the MAC and the asymmetry of star profiles by the coordinate x of the matrix. Similar systematic photometry errors for stars brighter than the critical value $V = 12.5^m$ were identified and analyzed in detail in [6] in the construction of the catalogue KMAC1. They were corrected using a rather complicated method. In the construction of the KMAC2, the program for the calculation of the intensity of star photocenters was modified. As a result, it was possible to shift the critical value V from 12.5^m to $V = 11.4^m$ and to ensure the measurement of photocenters of a sufficient number of Tycho-2 stars without systematic error.

The comparison with catalogues UCAC4 and CMC14 gave similar results. The resulting mean dependence of systematic differences $\Delta\delta$ on V was used as a systematic correction for the intermediate version of the catalogue KMAC2. Similarly, V values of the KMAC2 were calibrated by the catalogue UCAC4 using V values of the photometric survey of APASS [7].

Thus, at the same time, the systematic difference between photometric systems of the Tycho-2 catalogue, which we used as a reference one, and the Johnson standard system was eliminated [2].

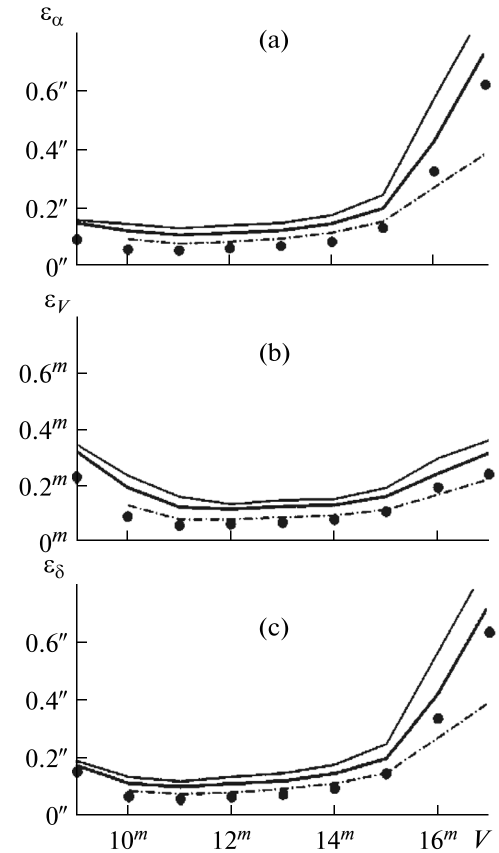

Fig. 4. Mean square differences between positions and V values in the comparison of the catalogue KMAC2 with catalogues UCAC4 and CMC14: for all the stars of the catalogue with the average number of observations $n = 2.8$ (bold line), for stars with $n = 1$ (thin line), and for $n \geq 4$ (dot-dash line). The formal error of the KMAC2 catalogue is shown by black circles.

The mean square value of ε of differences of positions KMAC2–UCAC4 and KMAC2–CMC14 characterizes the catalogue KMAC2 position error by the external consistency. The resulting estimates σ_n by both catalogues are almost identical, and their dependence on V for all stars in the catalogue with an average number of observations $n = 2.8$ is shown in Fig. 4 by the thick curve. For comparison, formal errors σ_n from the table that correspond to the average number of measurements of photocenters $n = 2.8$ are given (black circles). The excess of ε over σ_n can be explained by the contribution of random and systematic errors of catalogues of the comparison of UCAC4 and CMC14, as well as by systematic errors of KMAC2. Therefore, the real error of the KMAC2 catalogue is between ε and σ_n, i.e., in the region bounded by the thick curve and black circles in Fig. 4. For stars of $10–15^m$, where ε and σ_n are almost constant, the catalogue position error is close to 0.05–0.07″, and that for V values is within $0.05–0.08^m$. A larger error amount in comparison with estimates of 0.07″ and 0.05^m in [6] is caused by the lower number of observations of each star, on average 2.8 to 6, and the use of all available observations, including those with large Moon phases and under conditions of scattered clouds.

Stars with the Single Photocenter Detection

Figure 4 also shows dependences ε(V) for stars that have a large number ($n \geq 4$) of photocenter measurements. In comparison with the error ε for the full sample ($n = 2.8$), the value of ε for these stars is less by 20–30%. For stars with a single ($n = 1$) available measurement of the photocenter, the excess of the error is only 20%. The lack of repeated observations of these stars was partly caused by the fact that approximately 30% of the parts of the sky were scanned only once.

In addition, most of the objects with a single photocenter measurement have a magnitude that corresponds to the stars of $16–17^m$, are extremely faint for the MAC, and have a low detection probability. Most of these objects are not the real stars and are a result of the incorrect detection of the accidental increase

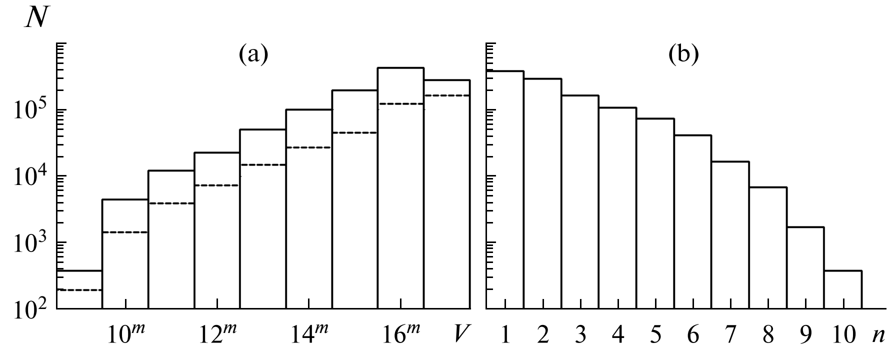

Fig. 5. Distribution of stars of the KMAC2 for magnitudes (a) $N(V)$ (the dotted line refers to the distribution of stars $n = 1$), (b) by the number of observations $N(n)$.

of the background level. Given the large, approximately 1.1×10^6 number of such photocenters, it was decided to keep them as part of the catalogue KMAC2, but only after filtering of fake objects by the comparison with other catalogues.

For this purpose, the use of catalogues NOMAD and CMC14 is most effective. In comparison with other catalogues, they have a large number of faint stars. With these catalogues, approximately 3.85×10^5 stars were identified with a single photocenter measurement (35% of the total number).

Figure 5 shows a histogram of the distribution of magnitudes $N(V)$ for all stars of the KMAC2 and stars with $n = 1$ measurement, as well as the distribution by the number of observations $N(n)$. The total number of stars in the catalogue KMAC2 is 1.09×10^6.

Catalogue Structure

In the catalogue, there are star coordinates α, δ for the equinox J2000.0 at the observation epoch, V values, number of measurements of the photocenter σ_n for each coordinate and for photometry, error of catalogue values σ_n by the internal consistency, and the observation epoch. Proper motions and their errors according to the catalogue NOMAD are also given.

CONCLUSIONS

The KMAC2 catalogue is the second catalogue obtained with the MAC telescope using the CCD camera. It was planned to obtain the astrometric survey of the equatorial zone by the fourfold overlapping of this area; however, for half the parts of the sky, it was possible to get only one- or twofold overlaps. This, however, did not affect significantly the final error of catalogue data (Fig. 5), and the achieved mean error of 0.05–0.07″ of star positions $11–14^m$ could be associated with errors of UCAC4 [12], CMC14 [3], and meridian circles in Bordeaux and Valinhos [11].

The obtained catalogue KMAC2 extends the reference system Tycho–HIPPARCOS to the limiting MAC magnitude $V = 17^m$ and provides a density of almost a thousand stars per square degree, which is significantly more than 1–5 stars of the Tycho-2 catalogue.

The catalogue was compiled using tools for the access of catalogues of the service Vizier (CDS, Strasbourg, France).

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