KYIV MERIDIAN AXIAL CIRCLE CATALOGUE (KMAC1) OF STARS IN FIELDS WITH EXTRAGALACTIC RADIO SOURCES

Yu. Babenko[1], **P. Lazorenko**[2], **V. Karbovsky**[2], **M. Buromsky**[1], **S. Kasjan**[1], **O. Denysyuk**[2]

[1] *Astronomical Observatory, National Taras Shevchenko University of Kyiv*
3 Observatorna Str., 04053 Kyiv, Ukraine
e-mail: babenko@observ.univ.kiev.ua

[2] *Main Astronomical Observatory, NAS of Ukraine*
27 Akademika Zabolotnoho Str., 03680 Kyiv, Ukraine
e-mail: laz@mao.kiev.ua

The catalogue of astrometric (positions, proper motions) and photometric (B, V, R, r', J) data of stars in 192 fields with the ICRF objects has been compiled at the Main Astronomical Observatory of the National Academy of Sciences of Ukraine and the Astronomical Observatory of the Kyiv National University. All fields are located in declination zone from 0° up to +30°; a nominal field size is $46'$ (right ascension) $\times\, 24'$ (declination). The observational basis of this work is 1100 CCD scans deep to $V = 17$ mag which were obtained with the Kyiv Meridian Axial Circle in 2001–2003 and which contain one million of images. Coordinates of star image centroids have been computed both as the weighted centers of gravity and as the linearized Gaussian profile fitting with unequal weights. Astrometric reductions have included corrections depending on image size fluctuations and position of a star on the CCD frame on the declination axis. A special approach was used for correction of magnitude-dependent errors since images of bright stars were oversaturated. The KMAC1 catalogue is presented in two versions. The KMAC1–T version contains 159 fields (104 796 stars) and was obtained with reduction to the Tycho-2 catalogue. For another 33 fields, the reduction was found to be unreliable due to a low sky density of the Tycho-2 stars. Therefore, transformation the second version of the KMAC1–CU to the ICRF was derived using the UCAC2 and CAMC13 catalogues as reference ones; it contains 115 032 stars in 192 fields and is of slightly better accuracy. As compared with the first version proper motions were derived using the USNOA2.0 catalogue as a first epoch catalogue. An external accuracy (based on comparison with UCAC2 and CMC13) of one catalogue position is about 60–70 mas for 14–15 mag stars. An average value of photometry error is better than 0.1 mag for stars to 16 mag.

INTRODUCTION

The Meridian Axial Circle (MAC, $D = 0.18$ m, $F = 2.3$ m) in Kyiv was recently modernized by installing a 1040×1160 CCD micrometer that can work in scan mode [6]. The micrometer designed at the Nikolaev Observatory (Ukraine) incorporates a glass filter to enable observations in the V band. With effective exposure of about 108 s for equatorial stars, the magnitude limit is $V_{lim} = 17$, and an internal precision of one observation in the optimal magnitude range of 12–14 mag is about $0.04''$–$0.1''$.

The instrument is used in the two observational projects aimed at extending the Hipparcos–Tycho reference frame to fainter magnitudes. The first project, now completed, concerns star fields in directions of 192 extragalactic ISRF objects in the declination zone from 0° up to +30°. The second, long-term project is the astrometric survey of the sky in equatorial zone from 0° up to +5° to obtain astrometric and photometric data for faint stars [6].

This report describes data reductions and compilation of the Kyiv Meridian Axial Circle Catalogue (KMAC1) of stars in fields of extragalactic radio reference frame sources. The KMAC1 is a catalogue of astrometric (α, δ, μ_α, μ_δ) and photometric (B, V, R, r', J) data for faint stars in 192 fields with ICRF objects. The catalogue was obtained in the framework of international programs: maintenance of the Hipparcos frame and link of optical frames to the ICRF. It was obtained in the framework of scientific cooperation between the Main Astronomical Observatory of the National Academy of Sciences of Ukraine and the Astronomical Observatory of the Kyiv National University. Besides of direct scientific aims the project allowed to develop infrastructure of the MAC

(experience in maintenance of electronics, optics adjusting, software for performing observations, database, software for reductions, experience in managing CCD data, *etc.*)

IMAGE PROCESSING

The basis of the catalogue is formed by 1100 scans each of $24.2' \times 46.5'$ size in the sky. Each of 192 fields was scanned at least five times. The scanned data was archived and stored to the CD database in the original form.

The data was processed performing next steps of reductions: image processing, removing instrumental errors, correction of the magnitude scale, reduction to the ICRF frame and, finally, compilation of the catalogue. A scheme of astrometric reductions and source catalogues used for compilation of the KMAC1 are shown in Fig. 1.

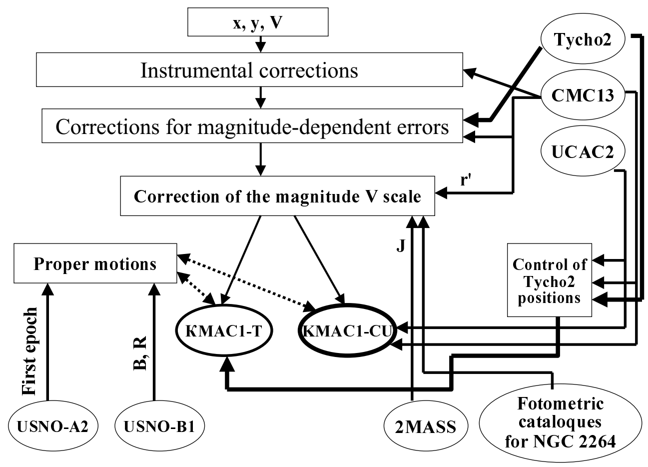


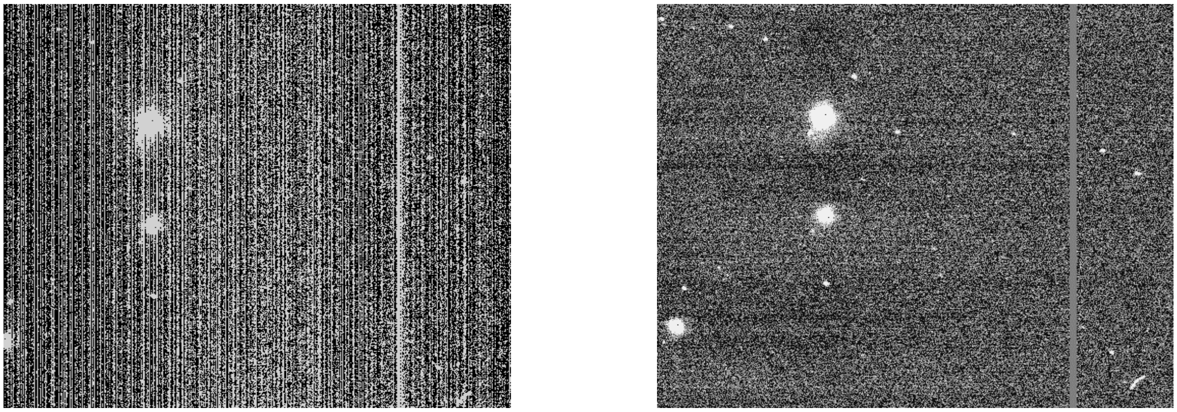
Figure 1. Compilation of the KMAC1: main steps of reductions and source catalogues

The first stage of the data reductions starts from a search and extraction of data files with a star field from the database archive. Then CCD images of stellar fields are filtered from various instrumental and noisy features which introduce inhomogeneity in a sky level. Inhomogeneity pattern inherent to a scan mode is dominated by the 1D strip-like structure (Fig. 2) which changes only along declinations (the x-axis on a CCD) with a possible weak trend over the y-axis (right ascensions). Besides a bias, read-out noise and sky background, the noisy structure of images are strongly affected by noise from a few dozen of bad bright pixels, which produces vertical one pixel width noisy strips. Images are also contaminated by a number of flares and treks from radioactive particles of the cosmic or Chornobyl origin which have coma or star-like shapes (see right low end in Fig. 2). It was found that noise sources contribute almost as additive factors (a similar conclusion was drawn in [2]). Therefore, scans were filtered out by means of subtracting running average taken, first, over the x-axis, and then in a perpendicular direction. Multiplicative noise component was found to be negligible. Filtration procedure realized as a one-pass program very efficiently clears images and yields almost a perfect constant sky level that does not show any variations across the image (Fig. 2).

Detection of objects in the noisy field was based on comparison of the pixel flux with a threshold defined as $I_{det} = [1.1 + (\sigma_n - 12)/45]\,\sigma_n$, where σ_n is a local sky noise. For better reliability, candidate images were preliminary convolved with a Point Spread Function (PSF) equal to a smoothed original star image [2]. It was required that an object should contain at least two adjacent pixels.

Determination of the star position x, y and the flux V of each object was performed with the two methods: 1) the modified center of gravity [2] and 2) the full profile fitting procedure based on the Gaussian linearized least squares method. The last method provided for both a circular and elliptical Gaussian model. The least squares solution was found using original non-smoothed images and, due to a high noise typical for this CCD, pixels were weighted depending on the pixel counts. The modified center of gravity positions were computed with images smoothed with a local PSF. The best solution giving final x, y, V values was chosen taking into account the image brightness and iteration convergence index.

All computations of x, y, V for the data array that contained more than one million of star images have been performed with an effective original software for about 1.5 hours.



a) Original scan

b) Scan after filtration

Figure 2. Example of a CCD sky scan filtration from a 1D strip structure; only a small part of a scan is shown

ASTROMETRIC REDUCTIONS

Astrometric reductions started from correcting measured x, y, V values for the instrumental errors of the MAC. This type of errors is related to oversaturation of bright (V < 12 mag) images and to a slight asymmetry of stellar profiles in a direction of the CCD x-axis. The amplitude of image distortions was found to depend on a star position (x coordinate) and its brightness. Distortions lead to a correlation of differences MAC–CMC13 in declinations with x and σ_x values, where σ_x is an image size parameter of the Gaussian model taken along the x-axis (Fig. 3). A similar effect is also seen in V magnitudes. To remove the correlation, we applied corrections to the measured x and V values in the form of a polinomial linear with respect to σ_x. Since the effect discussed depends on the star magnitude, the coefficient at σ_x was defined to be dependent on V. The model coefficient values were found as those which yielded the best intrinsic convergence of star declinations (or star magnitudes) computed for each scan. Note that this approach of reductions is sensitive only to the variable part of instrumental errors related to fluctuations of the computed σ_x values. The differences MAC–CMC13 in declinations computed after instrumental corrections do not show the presence of the correlation; besides, the variance of residuals had been reduced. Another effect of instrumental nature resulted in a systematic dependence of MAC–CMC13 differences (declinations and star magnitudes) on x. This error component was eliminated using computed differences of MAC–CMC13.

It should be noted that above approach to correction of instrumental errors has become possible due to the availability of the CMC13 catalogue which errors, of course, do not correlate with σ_x and x values measured at the MAC.

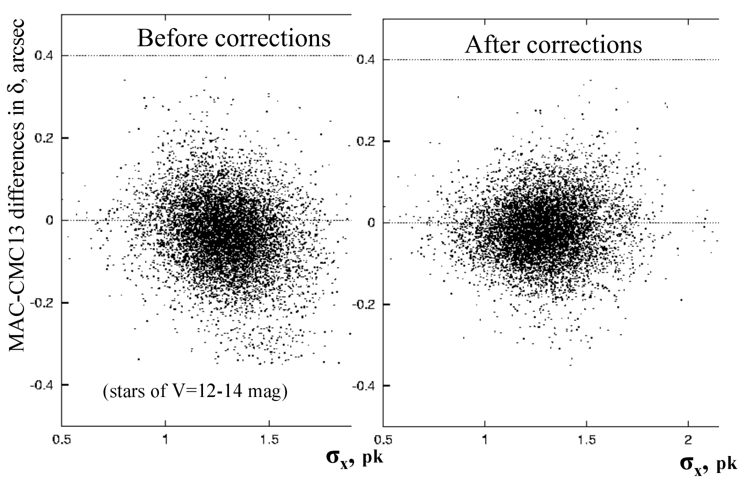


Figure 3. MAC–CMC13 differences in δ versus σ_x for the stars of 12–14 mag: before and after correction for instrumental errors

Described procedure is not sensitive to systematic magnitude-dependent errors in x, y and V; however, direct inspection of the MAC–Tycho-2 residuals clearly showed on the presence of this error. The systematic component of the MAC–Tycho-2 residuals was treated as errors in the MAC's data. Adequate corrections of x, y and V values were performed by subtracting the systematic effect, that was made, of course, only in the Tycho-2 magnitude range $V < 13$ mag.

More explicit analysis however has revealed a presence of seasonal variations in the MAC–Tycho-2 differences in δ as a function of V. Systematic part of these functions have been fitted with a model function and removed based on use of the Tycho-2 catalogue, again for stars with $V < 13$ mag.

REDUCTION TO THE ICRF

The corrected CCD position of stars originally were supposed to be reduced to the ICRF with use of the Tycho-2 catalogue as reference. Prior to this conversion we performed a tentative study to find how well positions of the Tycho-2 match with the CMC13 and UCAC2 [7]. For that purpose we compared the Tycho-2 star positions with those given in the CMC13, UCAC2 and in the preliminary version of the KMAC1 catalogue. Figure 4 presents individual differences of right ascensions of Tycho-2–CMC13, Tycho-2–UCAC2 shown versus Tycho-2–KMAC1 for 1843 Tycho-2 stars used as reference and with a restriction $|\mu_\alpha| < 0.3''/\mathrm{yr}$. One can notice a good agreement between three ground-based catalogues which provide positions normally consistent to $0.1''$–$0.2''$. Large deviations, usually for faint $V > 12$ mag stars, originate from errors in the Tycho-2 catalogue. For 1.4 percent of stars these errors exceed $\pm 0.5''$, and about 12% the errors are larger than $\pm 0.2''$.

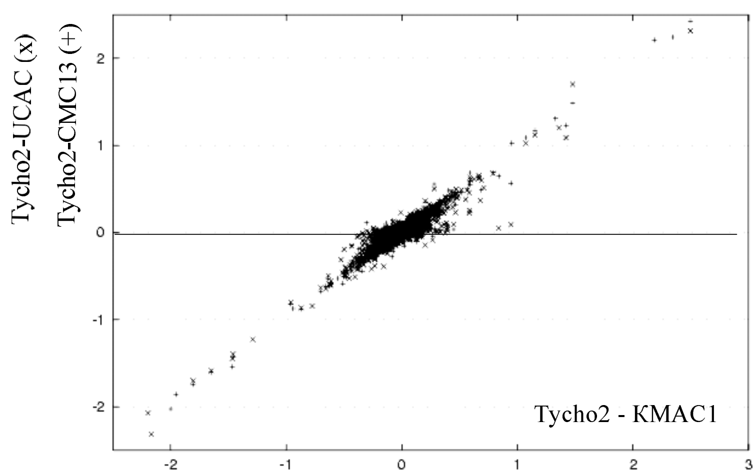


Figure 4. Tycho-2–CMC13 (+) and Tycho-2–UCAC2 (×) differences in right ascensions in comparison with the Tycho-2–KMAC1 differences

Taking into consideration results of the above analysis, one can conclude that a reduction to the ICRF using the Tycho-2 catalogue can be reliable providing that a number of reference stars is sufficiently large. In our case, due to a rather short scan length, some fields with a low star density contained just 6–8 Tycho-2 stars, which, of course, is insufficient for the purpose of a rigorous reduction. In addition, an accuracy of the reduction is often affected by inhomogeneous sky distribution of reference stars. To obtain more robust results, we used only those Tycho-2 stars whose positions, as found from a comparison with the CMC13 and UCAC2 catalogues, are precise to better than $\pm 0.2''$. In this case reliable results were obtained for 106 fields. For some other 53 fields, a good transformation to the ICRF required rejection of some reference stars with differences Tycho-2–CMC13 and Tycho-2–UCAC2 in the range from $\pm 0.2''$ to $\pm 0.15''$. A reduction procedure for another 33 fields with a low star density was found to give unstable results wildly reacting on the choice of a reference star set.

Thus, a reduction to the ICRF using the Tycho-2 catalogue was performed only for 159 sky fields with a high star density. A reliable conversion to the ICRF for the holy data array (192 sky fields) required the use of the CMC13 and UCAC2 catalogues which are also given in the ICRF system. Thus, the KMAC1 catalogue had been derived into the two versions: with reduction to the Tycho-2 (KMAC1–T) and with reduction to the CMC13 and UCAC2 catalogues (KMAC–CU).

CORRECTION OF THE *V* MAGNITUDE SCALE

Star magnitudes of the KMAC1 have been computed using measured V values which were corrected for the instrumental errors in a way described above. A zero point of the V magnitude scale was found using the Tycho-2 photometry of bright stars with $V < 13$ mag. The problem consisted in verification of the magnitude scale linearity which can not be directly controlled due to the absence of faint all sky standards in the V photometric band.

For this study we compared V values computed for stars of the open cluster NGC 2264 with those found in some photometric catalogues. The comparison indicated a systematic shift of magnitude scales up to 0.6 mag. Further analysis had shown that this error leads to a relative shift between positions of bright and faint stars in the two colour diagram $V - r' \sim V - J$. The effect was modelled and a necessary corrections applied to the V magnitudes for each star field.

CHARACTERISTICS OF THE KMAC1 CATALOGUE

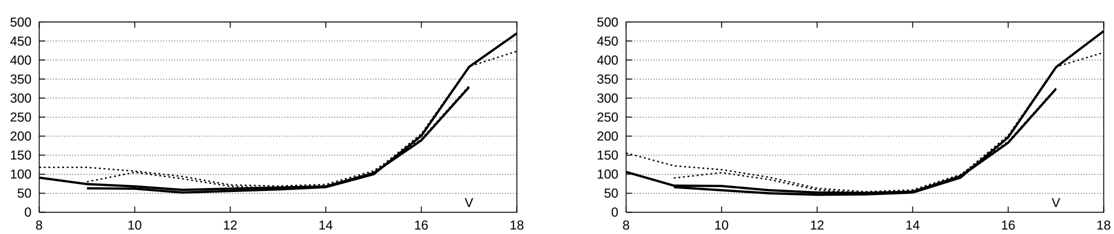
Besides of positions and original V values, the catalogue contains: B, R values copied from the USNO–B1 [5]; r' values taken from the CMC13; J values copied from the 2MASS [1]; proper motions were derived using positions in the USNO–A2.0 [4] as a first epoch, in doing this we used the USNO–B1 proper motions for cross-identification of stars. Main features of the KMAC1 are given in Table 1.

Table 1. Characteristics of the Kyiv Meridian Axial Circle Catalogue of stars in fields with extragalactic radio sources: versions KMAC1–T and KMAC1–CU

	KMAC1–T	KMAC1–CU
Reference catalogues	Tycho-2	CMC13, UCAC2
The number of fields	159	192
Declination zone	$0° \div +30°$	$0° \div +30°$
Nominal field size	$46' \times 24'$	$46' \times 24'$
Number of stars	104 796	115 032
V limiting	17 mag	17 mag
Spectral band	V (Johnson)	V (Johnson)
Precision of positions*	30–50 mas, $V < 14$ mag	30–50 mas, $V < 14$ mag
	160 mas, $V = 16$ mag;	160 mas, $V = 16$ mag
Precision of photometry*	0.03–0.05 mag, $V < 15$ mag	0.03–0.05 mag, $V < 15$ mag
External catalogue error**	50–70 mas, $V < 14$ mag;	40–60 mas, $V < 14$ mag;
	200 mas, $V = 16$ mag;	190 mas, $V = 16$ mag;
Mean epoch	2002.3	2002.3

*) Internal errors
**) Found from residuals
KMAC1–CMC13 and KMAC1–UCAC2

Astronomical data included: α, δ, μ_α, μ_δ, B, V, R, r', J



a) External errors of the KMAC1–T

b) External errors of the KMAC1–CU

Figure 5. External error of the KMAC1 (versions "T" and "CU") positions estimated as a rms difference with the CMC13 and UCAC2 positions; solid lines – in right ascensions; dashes – in declinations; it is not specified which plot refer to the CMC13 or UCAC2 since the results are very similar in both cases

External error of the KMAC1–T and KMAC1–CU positions estimated as a rms difference of this catalogue positions with the CMC13 and UCAC2 are shown in Fig. 5. Systematic errors, with reference to the CMC13 and UCAC2, do not exceed ± 20 mas.

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