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Protsyuk, Yu., Kovalchuk, A., and Mazhaev, A.

Research Institute «Mykolaiv Astronomical Observatory», 1, Observatorna St., Mykolaiv, 54030, Ukraine, tel. +380 512 477 014

CATALOG OF POSITIONS AND PROPER MOTIONS OF STARS IN THE VICINITY OF OPEN CLUSTERS

A catalog of positions and proper motions of stars in 544 square areas of nearly (1×1)° around the Galactic open clusters has been created using photographic and CCD observations, at Research Institute «Mykolaiv Astronomical Observatory» (RI «MAO»). To this end, 293 plates of (5×5)° obtained with the MAO Zonal Astrograph (D=116 mm, F=2040 mm) in 1962—1993 and more than 20 thousand CCD frames (0.7×0.7)° obtained with KT-50 telescope (D=500 mm, F=3000 mm) in 2011—2015 have been used. Almost 270 thousand FITS files from the IVOA image archives with observational epoch from 1953 to 2010 have been downloaded and processed. The created catalogue contains more than 2.3 million stars having a magnitude of (7.5—18.5)^m in the ICRS system, with accuracy of positions for both coordinates ranging from 0.02" to 0.05". Internal accuracy of proper motions is estimated as ~0.004"/year.

Keywords: CCD-observations, open clusters, catalogue of positions and proper motions of stars.

For creating the catalog of precise positions and proper motions epoch difference between the moments of observations is as important as accuracy of observations. Therefore, for the purpose of this research, it was decided to use both photographic observations made at RI «MAO» in 1960—1990, images of astronomical databases (ADB) of International Virtual Observatory Alliance (IVOA), and modern charge-coupled device (CCD) observations.

Catalog of 1766 open clusters VII/229 [1] with recent updates was selected as basic catalog. Using its data, a cross-search with MAO photographic plate database [2] was done and all plates with images of the sky within ±20° from the galactic plane comprising open clusters with a catalog size over 3' have been found. Totally, 354 candidates in the respective areas were selected from the plate archive, then the photographic plates were visually analyzed using database of preview images [3]. As a result, the final list of 320 areas was selected and respective plates from the RI «MAO» archive were scanned in 2011—2014.

To create a list of sky areas for CCD observations and search in ADB, catalog of open clusters VII/229 [1] with the same criteria for the plates was used. As a result, a list of 544 areas with open clusters has been obtained.

PROCESSING OF PHOTOGRAPHIC IMAGES

To determine the star coordinates, before scanning, the photographic plate was cleaned from previous inscriptions made on the glass side. Scanning was done using *Epson Perfection V750 Pro* with a resolution of 1200 and 1600 dpi (Dots Per Inch) and saving into FITS (Flexible Image Transport System) format. To select the optimal mode of scanning and processing a special study has been made [4]. For 20×20 cm plates and the use of our own software package the most suitable resolutions are 1200 dpi (as the fastest version with a sufficient accuracy) and 1500—1600 dpi (with an acceptable processing rate and better accuracy). Assuming that computers every year get more powerful (especially in terms of available disk space), it has been decided to change the basic resolution for the processing from 1200 dpi

(merger of 4 physical pixels of scanline) to 1600 dpi (merger of 3 physical pixels of scanline). Usually, each plate is scanned 6 times with saving data in 16-bit FITS format. Scanning is performed with emulsion, downward, with a linear γ-curve in scanner settings.

The primary treatment of observations includes automatic account of specific features of individual images (veil, uneven background, image defects, etc.), automatic digital filtering, restoration of defective star images, search of star-like objects, and determination of coordinates in the rectangular coordinate system of CCD frame. The primary processing is done in Linux OS and is described in detail in [5—8].

Further processing takes place in Windows OS. The stars are identified in reference catalogs with further astrometric reduction to determine the equatorial coordinates of all registered objects [8, 9]. The reduction is done in several iterations. General algorithm for processing of plates was developed in 2010—2012 [8]. After this, the algorithm has remained practically unchanged, but capabilities of individual programs have been expanded and the computerization has been added using the scripts of frequently repeated operations.

Today, the software package [8] can process images with a resolution of 600—4800 dpi, up to 32,000×32,000 pixels or up to (50×50)°, which comprise up to 2.5 million objects. For the peak operation it is enough to have any PC with 4 GB RAM. The package has been successfully used for obtaining several catalogs and coordinates of the Solar system objects [9, 10, 11]. In 2013—2016, over 8000 scanned images in different projections obtained at six different observatories were processed using the package.

CCD OBSERVATIONS AND OBSERVATIONS FROM IVOA ARCHIVES

The observations for obtaining a catalog of positions for current epoch were held using the KT-50 *Mobitel* telescope [12]. According to the list of 544 areas with open clusters, in 2011—2015, during 173 nights, over 20 thousand CCD observations were received in 2900 strips in 460 areas with open clusters. The total volume of observations exceeds 350 GB. The average number of observations of one strip is about 6.5 times. The strip is sequence of CCD frames having a width of about 42.5" exposed serially by right ascension in drift-scan mode. The length of each frame depends on the exposure time. In this case, at an exposure of 20 seconds it amounts to 39.5". If cluster is expected to have a significant size, additional observations are made with a required shift and an increment of 20" by declination in both directions. For processing the observations in the system of UCAC4 catalog [13], the *Astrometrica* [14] and cubic reduction model are used. The program settings for magnitude use R-band since the telescope is equipped with a filter close to the R-band.

For expanding the possible combinations of observation epochs a software was developed for automatic search and download of the images of sky areas from ADB according to given criteria [15]. This has made it possible to download images from Aladin Images Server [16], infrared photometric reviews 2MASS [17] and DENIS [18], Digitized Sky Survey [19, 20], and WISE 4-Band AllSky Atlas [21] from different servers. Totally, in 2014—2015, about 270 thousand images in FITS-format were downloaded. The images were processed using *Astrometrica* in the system of UCAC4 catalog. Settings and options for different telescopes were determined separately. The additional data from various epochs in the form of images were used in order to process them by the same software in a single reference catalog system. This should reduce the systematic difference in stellar coordinates obtained using different instruments.

To handle large data arrays a complex of 10 virtual machines on two PC was established for simultaneous automatic processing of the array using an application for *Astrometrica* developed at RI «MAO». Totally, the processing of all 270 thousand images took nearly 17 round-the-clock days. It would take 170 days using one PC and more than a year if to process only during working hours.

PHOTOGRAPHIC CATALOG OF STELLAR COORDINATES FOR THE 1ST EPOCH

While processing the images of photographic plates it was found that a part of images significantly deviated from the standard observation method. Therefore, 293 plates were used for the catalog. Totally, over 1700 images with a resolution of 1200 and 1600 dpi have been processed and more than 30 million records have been obtained. Based on these materials, using specially developed software, a catalog of positions of 2.7 million stars having a magnitude of $(6—16)^m$ (Fig. 1, *a*) in Tycho2 system with a mean position accuracy of 0.09" for right ascension and 0.10" for declination (Fig. 1, *b*) has been created. The catalog mean epoch is 1983.6.

CCD CATALOG OF STELLAR POSITIONS FOR THE 2ND EPOCH

CCD frames were processed using *Astrometrica* [13] and additional applications developed at RI «MAO» for package processing. Over 20 thousand CCD frames have been processed in the UCAC4 system. More than 93 million observations of objects in areas have been obtained. Based on these materials an astrometric position catalog for 4.2 million stars with a magnitude of $(7.5—17)^m$ has been created. The stars were observed 3 times and more with an average of about 20 times. Mean accuracy of coordinates for the stars up to 16^m is 32 mas for right ascension and 42 mas for declination (Fig. 2, *a*). The mean epoch of CCD catalog is 2013.6.

Fig. 2, *b* shows distribution of catalog accuracy by declination. One can see that the accuracy parameters of KT50 *Mobitel* telescope get worse while deviating from zenith, with accuracy for declination degrading much higher as compared with that for right ascension. This could be caused by insufficient adjustment of the telescope, which usually is done towards zenith ($\delta = 47°$) and pole ($\delta = 90°$) or by light pollution from the city above horizon, which leads to an increase in background brightness and decrease in *signal/noise* ratio for stars.

STELLAR COORDINATE CATALOGS BASED ON PROCESSING OF IMAGES OBTAINED FROM IVOA RECORDS

Images obtained from ADB IVOA were processed using *Astrometrica* and additional applications developed at RI «MAO» for package processing. Over 270 thousand images have been processed in the UCAC4 system. The whole data were divided into five arrays from which separate catalogs for six various epochs have been obtained.

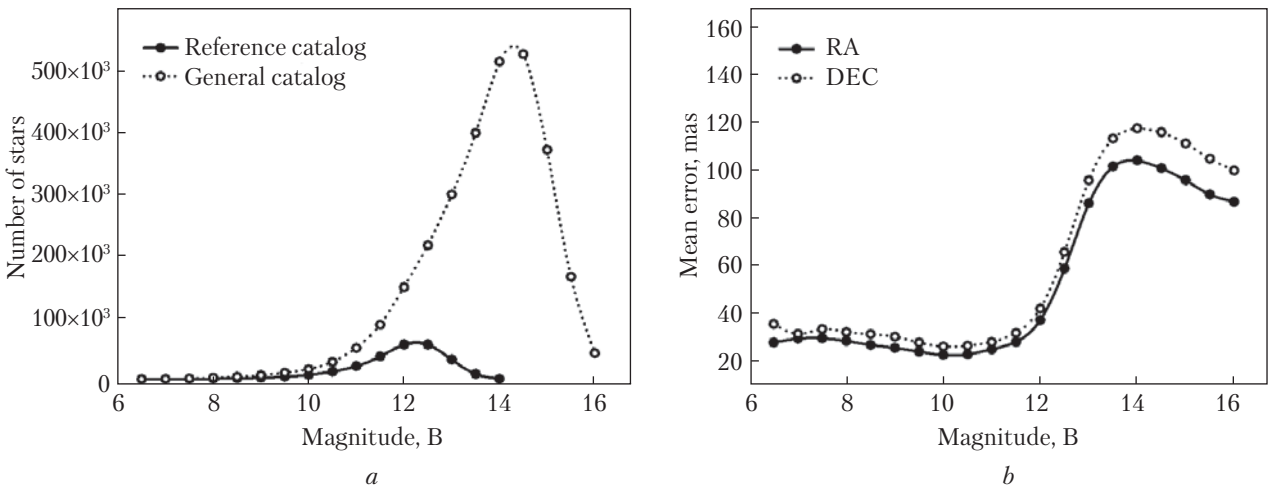

Fig. 1. Distribution of stars from photographic catalog by magnitude (*a*); dependence of accuracy of photographic catalog on magnitude (*b*)

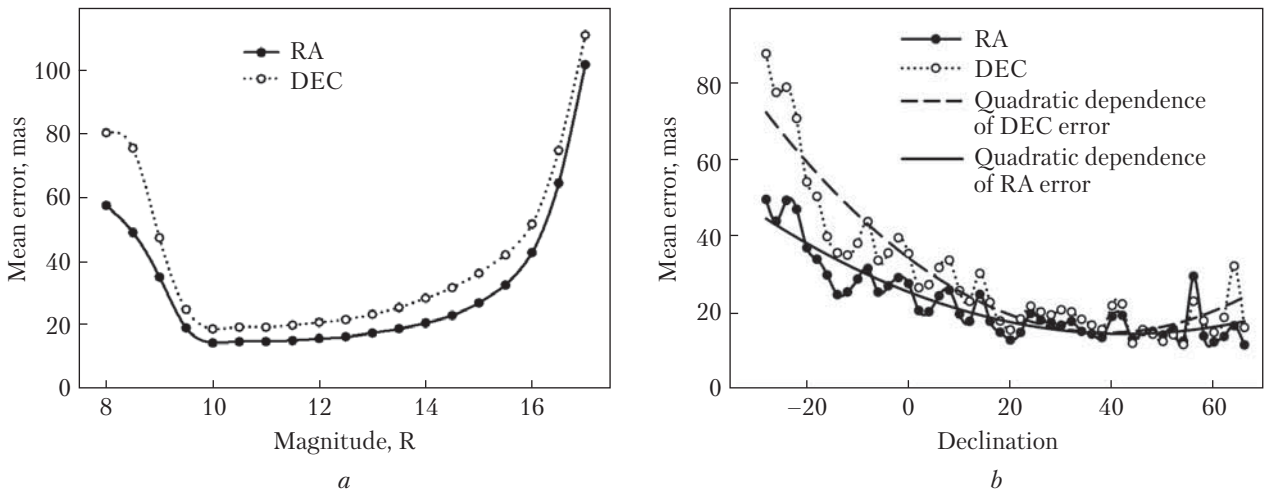

Fig. 2. Dependence of accuracy of CCD catalog on magnitude (*a*) and declination (*b*)

Having processed the images from 2MASS [16], over 139 million observations of objects in areas containing open clusters were obtained. Based on these data an astrometric position catalog for 20.2 million stars with a magnitude of (8—19.5)^m has been created. The stars were observed 3 times and more with an average of about 6.3 times. Mean accuracy of stellar coordinates is 41 mas for right ascension and 40 mas for declination. The catalog mean epoch is 1998.7.

Having processed the images from DENIS [17], over 26 million observations of objects in areas containing open clusters were obtained. Based on these data an astrometric position catalog for 3.2 million stars with a magnitude of (8—19.5)^m has been created. The stars were observed 3 times and more with an average of about 5.2 times. Mean accuracy of stellar coordinates is 52 mas for right ascension and 67 mas for declination. The catalog mean epoch is 1998.8.

Having processed the images from DSS-A [18], over 19.7 million observations of objects in areas containing open clusters were obtained. Based on these data an astrometric position catalog for more than 3 million stars with a magnitude of (12—19)^m has been created. The stars were observed 3 times and more with an average of about 4.1 times. Mean accuracy of stellar coordinates is 66 mas for right ascension and 70 mas for declination. It should be noted that for the stars brighter than 16^m a material impairment of accuracy is reported. The catalog mean epoch is 1953.2.

The DSS-B images [19] were divided into two arrays: the images made before and those made after 1995.

For the first array more than 53.5 million observations of objects in areas containing open clusters were obtained. Based on these data an astrometric position catalog for more than 8.1 million stars with a magnitude of (12—19)^m has been created. The stars were observed 3 times and more with an average of about 5.7 times. Mean accuracy of stellar coordinates is 47 mas for right ascension and 53 mas for declination. It should be noted that for the stars brighter than 16^m a material impairment of accuracy is reported. The catalog mean epoch is 1988.3, which is close to the epoch of our photographic catalog. The distribution of accuracy for right ascension and declination has some dependences in terms of accuracy difference for the former and the latter, with the situation resembling behavior of *Mobitel* telescope system with zero-point near equator. Moving northward the accuracy difference between the coordinates increases.

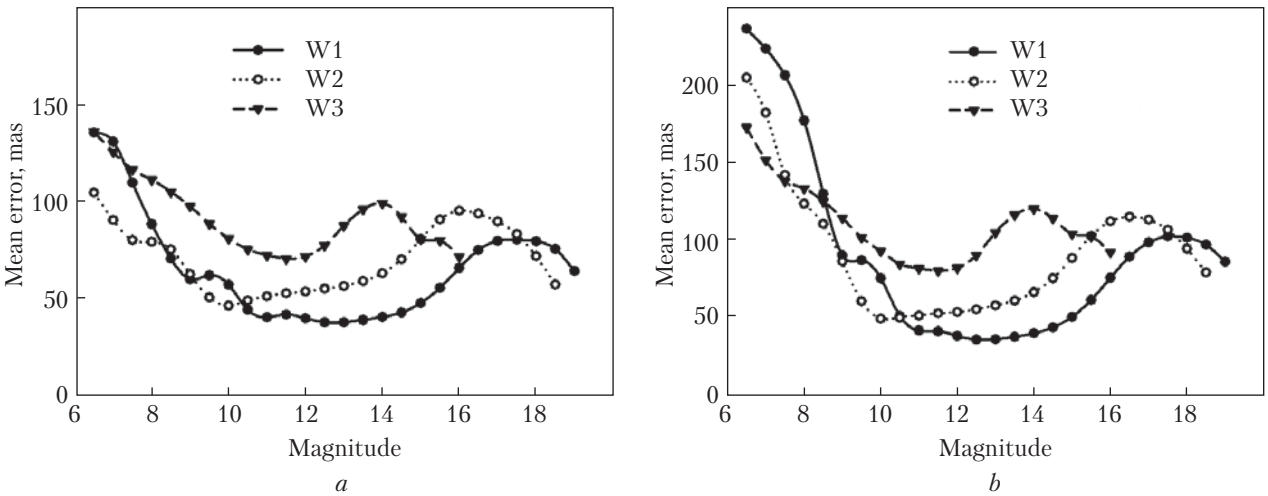

Fig. 3. Dependence of accuracy of WISE Survey catalogs on magnitude for right ascension (*a*) and declination (*b*)

For the second array more than 11.7 million observations of objects in areas containing open clusters were obtained. Based on these data an astrometric position catalog for more than 1.1 million stars with a magnitude of $(12-19)^m$ has been created. The stars were observed 3 times and more with an average of about 4.3 times. Mean accuracy of stellar coordinates is 35 mas for right ascension and 36 mas for declination. It should be noted that for the stars brighter than 16^m a material impairment of accuracy is reported. The catalog mean epoch is 1996.7.

WISE images [20] were divided into 4 arrays obtained at different wavelengths (W1, W2, W3, and W4). The fourth array was not handled because of small number of stars and large errors. The first three were processed and their accuracies were compared (Fig. 3). Improvement of accuracy in the area of faint magnitudes for all arrays in Figure shows a virtual or noise nature of objects beyond boundary magnitudes of the arrays at extreme points. Above this magnitude, *signal/noise ratio* is low and the number of objects is still quite large, which leads to appearance of pseudo-stars. Also, this can partially characterize a noise level in separate spectral bands. Average epoch of all catalogs is 2010.3, which is close to the epoch of our CCD catalog. For the W1 array, more than 140 million observations of objects in areas containing open clusters were obtained. Based on these data an astrometric position catalog for more than 9 million stars with a magnitude of $(7-19.5)^m$ has been created. The stars were observed 4 times and more with an average of about 14 times. Mean accuracy of stellar coordinates is 56 mas for right ascension and 64 mas for declination.

For the W2 array, more than 123 million observations of objects in areas containing open clusters were obtained. Based on these data an astrometric position catalog for more than 7.5 million stars with a magnitude of $(7-19.5)^m$ has been created. The stars were observed 4 times and more with an average of about 14 times. Mean accuracy of stellar coordinates is 74 mas for right ascension and 83 mas for declination.

For the W3, more than 17.1 million observations of objects in areas containing open clusters were obtained. Based on these data an astrometric position catalog for more than 1.1 million stars with a magnitude of $(6-17)^m$ has been created. The stars were observed 4 times and more with an average of about 14 times. Mean accuracy of stellar coordinates is 89 mas for right ascension and 106 mas for declination.

Since the W3 array has the worst accuracy and a small amount of stars it has been excluded

from further consideration for the creation of proper motion catalog.

CATALOG OF STELLAR POSITIONS AND PROPER MOTIONS IN AREAS AROUND OPEN CLUSTERS (NAO2015pm)

Having processed the images obtained using various telescopes in different epochs 8 individual catalogs for observation epoch and equinox J2000.0 (see Table) in ICRS system have been obtained.

For creating new catalog of positions and proper motions NAO2015pm a software was developed to search for common stars in various input catalogs and to determine their proper motions by solving the system of equations with the use of least square method:

$$\alpha = a1 + b1 \times (\text{epoch-2000});$$
$$\delta = a2 + b2 \times (\text{epoch-2000}). \quad (1)$$

Having solved the system of equations (1) for each star and found the coefficients $a1$, $b1$, $a2$, and $b2$, the proper motions are obtained from the formulas:

$$\mu_\alpha = b1 \times \cos(\delta);$$
$$\mu_\delta = b2, \quad (2)$$

and the coordinates for J2000 epoch are obtained from the formulas:

$$\alpha_{2000} = a1;$$
$$\delta_{2000} = a2. \quad (3)$$

To raise accuracy of proper motions the program has three limitations, namely: the star shall be simultaneously presented in catalogs for epochs before and after 2000, have an epoch difference larger than three years between individual reference points (all reference points with a difference of up to 3 years are averaged) and, at least, three reference points for different epochs.

The magnitudes in *R*-band are used as reference magnitudes. For identification of stars from various catalogs deviations up to 3.5^m with respect to average magnitude and up to 2.5" with respect to average coordinates are allowed. Each catalog has its boundary magnitude to prevent inclusion of noise objects in the final catalog. As a result, a catalog of positions, proper motions, and magnitudes for over 2.3 million stars $(7.5—18.5)^m$ in rectangular areas of approximately $(1\times1)°$ (Fig. 4, *a*) observed during three and more epochs has been created. The average number of observation epochs for each star is about 3.5; mean accuracy is 35 mas for right ascension and 40 mas for declination. Dependence of coordinate accuracy on magnitude is showed in Fig. 4, *b*. The lesser average accuracy for magnitude of $(12—15)^m$ is explained by influence of stars from photographic observations. For ZON1 catalog (Table), accuracy gets much worse starting with a magnitude of 12^m, but after 15^m the number of such stars decreases sharply (Fig. 1), whereas for DSS1 catalog, accuracy worsens for the stars brighter than 16^m. The coordinates in catalog are given for epoch and equinox J2000.0. The magnitude is given as estimate because no additional photometric studies were done while preparing the catalog. Average accuracy of proper motions is estimated as 3.9 mas/year for right ascension and 4.1 mas/year for declination. Dependence of proper motion accuracy on magnitude is given in Fig. 4, *c*. One can see that the accuracy of proper motions is in good correlation with that of stellar coordinates in the catalog (Fig. 4, *b*).

COMPARATIVE ANALYSIS OF PROPER MOTIONS FOR COMMON STARS BETWEEN NAO2015pm CATALOG AND TYCHO2 AND XPM

The proper motions from NAO2015pm have been compared with those of Tycho2 and XPM using our software. The average difference between the common stars from NAO2015pm and XPM is found to be about -0.3 ± 9.4 mas/year for right ascension and $+0.5 \pm 10.1$ mas/year for declination; more than 1.3 million common pairs have been identified. The difference in proper motions of common stars between NAO2015pm and Tycho2 is established to be about +0.3 ±6.1 mas/year for right ascension and +2.0 ±6.7 mas/year for declination; 24 thousand common stars have been identified. Distribution of

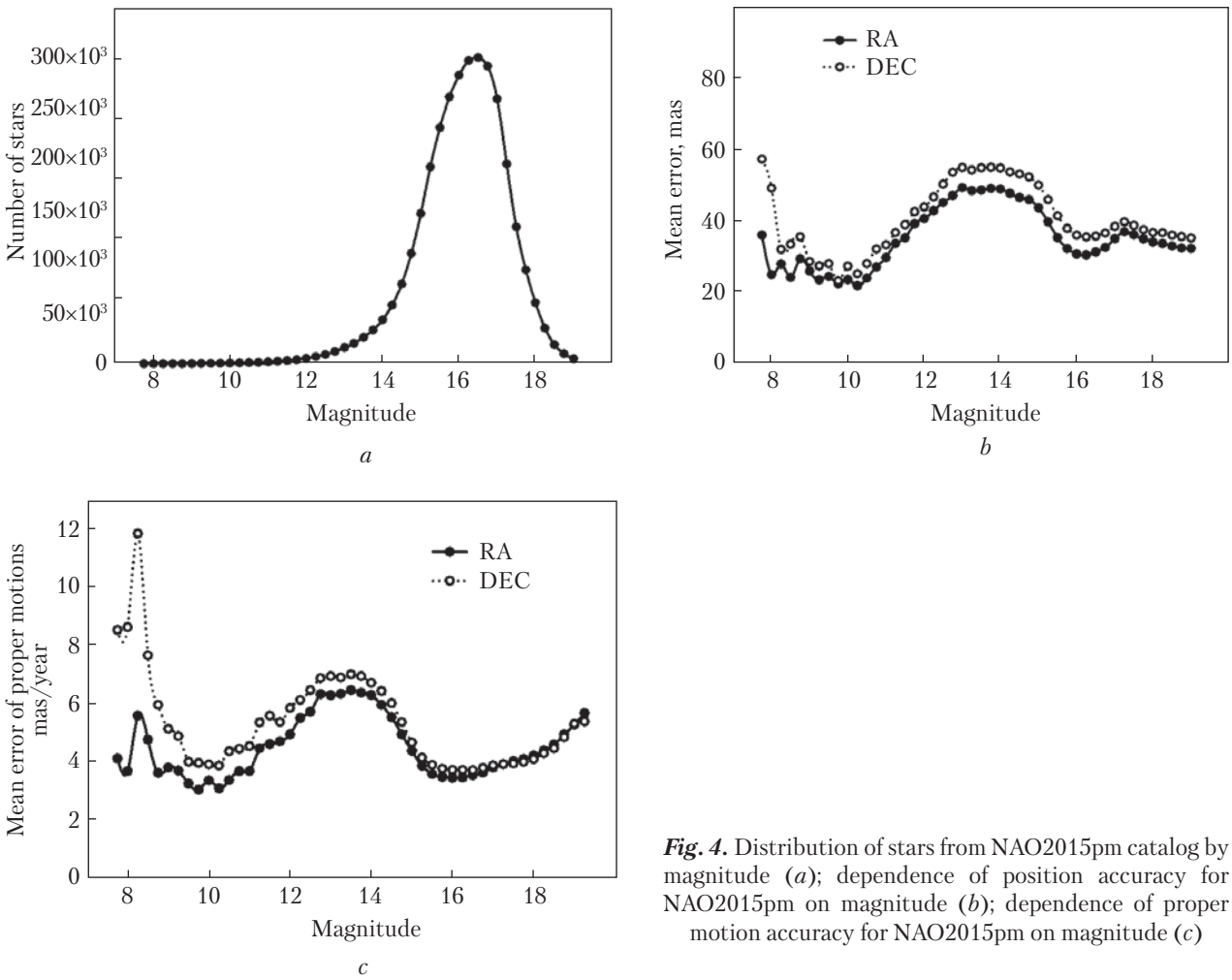

Fig. 4. Distribution of stars from NAO2015pm catalog by magnitude (*a*); dependence of position accuracy for NAO2015pm on magnitude (*b*); dependence of proper motion accuracy for NAO2015pm on magnitude (*c*)

Intermediate Catalogs Used for Creation of the Catalog of Positions and Proper Motions NAO2015pm

№	Catalog	Average epoch, year	Number of stars, million	Mean accuracy RA, mas	Mean accuracy DEC, mas	Scale, "/pixel
1	ZON1	1983.6	2.7	93.7	106.3	2.13
2	MBT1	2013.6	4.2	51.5	60.9	0.83
3	MAS1	1998.7	20.2	40.6	40.1	1
4	DNS1	1998.8	3.2	51.8	66.5	0.99
5	DSS1	1953.2	3.0	65.7	70.1	1.7
6	DSS2	1988.3	8.1	46.6	52.9	1.7
7	DSS3	1996.7	1.1	34.6	36.4	1.7
8	WIS1	2010.3	9.1	56.4	64.1	2.75
	Total		51.6	55.1	62.2	

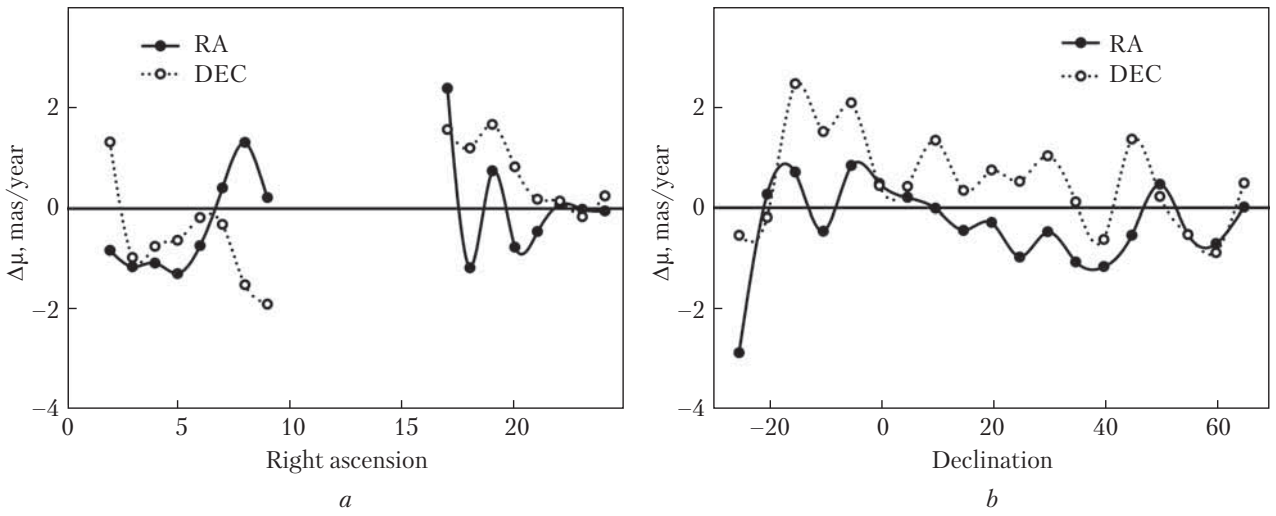

Fig. 5. Distribution of systematic difference (Δμ) between the stars from NAO2015pm and from XPM by right ascension (*a*) and by declination (*b*)

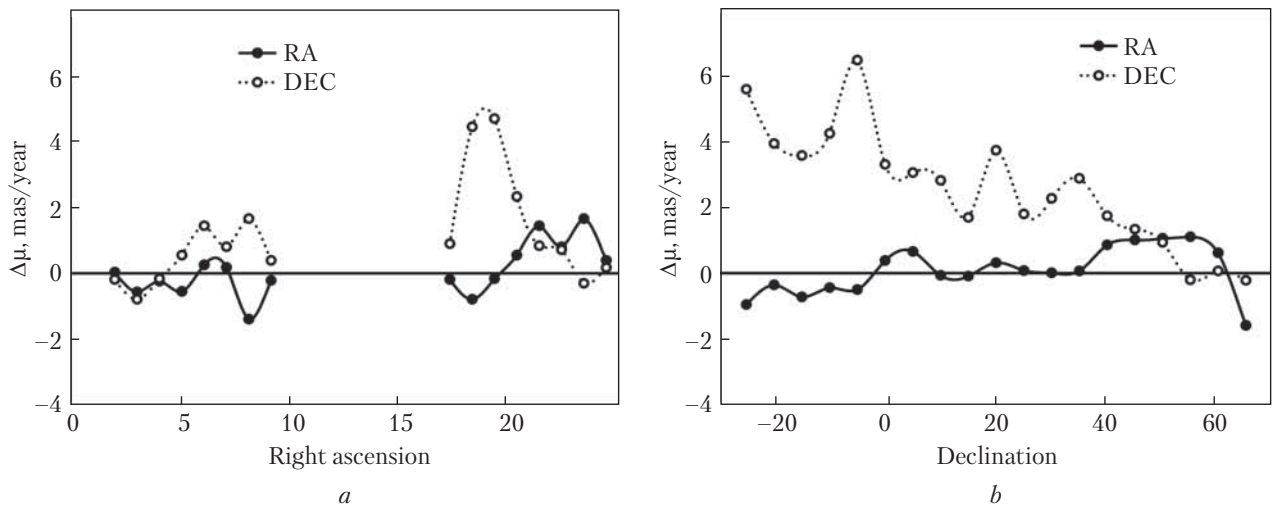

Fig. 6. Distribution of systematic difference (Δμ) between the stars from NAO2015pm and Tycho2 by right ascension (*a*) and by declination (*b*)

systematic difference between NAO2015pm and XPM is showed in Fig. 5; that of between NAO2015pm and Tycho2 s presented in Fig. 6. The data are averaged with a step of one hour for right ascension and 5° for declination. The NAO2015pm catalog has better systematic difference in proper motions with XPM than with Tycho2. Absence of data within the range of right ascensions from 9 to 17 hours is caused by lack of observations for declinations lower than −20°, at RI «MAO».

Liner correlation of proper motions from NAO2015pm and those form Tycho2 and XPM has been studied as well. In this case, NAO2015pm has showed better correlation with Tycho2 as compared with XPM, since the NAO2015pm + Tycho2 sample has brighter stars. The correlation with XPM gets worse for declination less than 5°.

If this area is excluded, linear correlation coefficients (LCC) for proper motions are 0.66 for right ascension and declination. The LCC for NAO2015pm and Tycho2 for the same area are 0.69 and 0.75, respectively.

The second comparison of proper motions (PM) was made using TopCat. Firstly, a file containing 23 721 pairs of common stars for the two catalogs (NAO2015pm and Tycho2) was created. After this, a comparative analysis for the pairs was made with LLC estimated as $r = 0.74$ for right ascension and $r = 0.78$ for declination. Also, equations of PM linear correlation for right ascension and declination for the pairs of common stars were obtained:

$$\mu_{\alpha 2} = 0{,}66 \times \mu_{\alpha 1} - 0{,}25;$$
$$\mu_{\delta 2} = 0{,}69 \times \mu_{\delta 1} - 2{,}8, \qquad (4)$$

where $\mu_{\alpha 1}$ — PM for right ascension in the MAO catalog; $\mu_{\alpha 2}$ — PM for right ascension in Tycho2; $\mu_{\delta 1}$ — PM for declination in the MAO catalog; and $\mu_{\delta 2}$ — PM for declination in Tycho2.

To analyze PM in NAO2015pm and XPM using TopCat a file containing 1 400 480 pairs of common stars within the range of declination from 10 to 60° was created. After this, a comparative analysis was made with LCC estimated as $r = 0.63$ for right ascension and $r = 0.63$ for declination, for all pairs of common stars. Also, equations of PM linear correlation for right ascension and declination for the pairs of common stars were obtained:

$$\mu_{\alpha 2} = 0{,}76 \times \mu_{\alpha 1} + 0{,}01;$$
$$\mu_{\delta 2} = 0{,}70 \times \mu_{\delta 1} - 0{,}85, \qquad (5)$$

where $\mu_{\alpha 1}$ — PM for right ascension in the MAO catalog; $\mu_{\alpha 2}$ — PM for right ascension in XPM; $\mu_{\delta 1}$ — PM for declination in the MAO catalog; $\mu_{\delta 2}$ — PM for declination in XPM.

CONCLUSIONS

Several hundreds of million original stellar coordinates in the area ±20° from the Galaxy plane with a difference in average epochs varying from 25 to 60 years have been obtained. The coordinates have been used for determination of proper motions. Based on processed images obtained from IVOA archives six catalogs of positions of stars having a magnitude of $(7—19)^m$ for various average epochs from 1953 to 2010 have been composed. The total number of stars covered exceeds 50 million; mean accuracy of position varies from 0.03" to 0.07".

New catalogs of positions have been created: 2.7 million stars having a magnitude of $(7—16)^m$ for the average epoch J1983.2 and equinox J2000 based on photographic observations and 4.2 million stars having a magnitude of $(8—17)^m$ for the average epoch 2013.6 and equinox J2000 based on CCD observations.

A catalog of positions and proper motions of over 2.3 million stars having a magnitude of up to 18m in 544 selected areas with open clusters has been created using modern highly precise observations and photographic observations made in the second half of the 20th century. Mean accuracy of catalog positions for both coordinates for various magnitudes ranges from 0.02" to 0.05", mean accuracy of proper motions is about 0.004"/year for both coordinates.

The obtained accuracy of coordinates and proper motions corresponds to the world standards of accuracy for terrestrial observations. Also, the catalog includes stars from open clusters of the Galaxy, which enables to get more accurate data on their stellar population and average proper motions.

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Ю.І. Процюк, О.М. Ковальчук, О.Е. Мажаєв

Науково-дослідний інститут
«Миколаївська астрономічна обсерваторія»,
вул. Обсерваторна, 1, Миколаїв, 54030, Україна,
+380 512 564 040

КАТАЛОГ ПОЛОЖЕНЬ ТА ВЛАСНИХ РУХІВ ЗІР НАВКОЛО РОЗСІЯНИХ СКУПЧЕНЬ

В НДІ «МАО» створено каталог NAO2015pm положень та власних рухів зір у 544-х прямокутних ділянках розміром приблизно $(1\times1)°$ навколо розсіяних скупчень з використанням фотографічних та ПЗЗ-спостережень. Для цього було використано 293 пластинки $(5\times5)°$, отриманих на зонному астрографі «МАО» (D = = 116 мм, F = 2040 мм) у 1962—1993 рр. та понад 20 тис. ПЗЗ-кадрів $(0{,}7\times0{,}7)°$, отриманих на телескопі КТ-50 (D = 500 мм, F = 3000 мм) у 2011—2015 рр. Також було оброблено майже 270 тис. файлів зображень з баз даних Міжнародного альянсу віртуальних обсерваторій з епохами спостережень від 1953 до 2010 рр. Каталог NAO2015pm включає понад 2,3 млн зір $(7{,}5—18{,}5)^m$ у системі ICRS з середньою точністю положень (0,02—0,05)". Середня внутрішня точність власних рухів — ~0,004"/рік.

Ключові слова: ПЗЗ-спостереження, розсіяні скупчення, каталог положень та власних рухів зір.

Ю.И. Процюк, А.Н. Ковальчук, А.Э. Мажаєв

Научно-исследовательский институт
«Николаевская астрономическая обсерватория»,
ул. Обсерваторная, 1, Николаев, 54030, Украина,
+380 512 564 040

КАТАЛОГ ПОЛОЖЕНИЙ И СОБСТВЕННЫХ ДВИЖЕНИЙ ЗВЕЗД В ОКРЕСТНОСТЯХ РАССЕЯННЫХ СКОПЛЕНИЙ

В НИИ «НАО» создан каталог NAO2015pm положений и собственных движений звезд в 544-х прямоугольных площадках размером приблизительно $(1\times1)°$ вокруг рассеянных скоплений с использованием фотографических и ПЗС-наблюдений. Для этого было использовано 293 пластинки $(5\times5)°$, полученных на зонном астрографе «НАО» (D = 116 мм, F = 2040 мм) в 1962—1993 гг., и более 20 тыс. ПЗС-кадров $(0{,}7\times0{,}7)°$, полученных на телескопе КТ-50 (D = 500 мм, F = 3000 мм) в 2011—2015 гг. Также были обработаны около 270 тыс. файлов изображений из баз данных Международного альянса виртуальных обсерваторий с эпохами наблюдений от 1953 до 2010 гг. Каталог NAO2015pm включает более 2,3 млн звезд $(7{,}5—18{,}5)^m$ в системе ICRS со средней точностью положений (0,02—0,05)". Средняя внутренняя точность собственных движений — ~0,004"/год.

Ключевые слова: ПЗС-наблюдения, рассеянные скопления, каталог положений и собственных движений звезд.