# THE FONAC CATALOGUE AS A RESULT OF THE FON PROJECT

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The technique for constructing the first version of the astrographic catalogue FONAC 1.0 based on the measurements of the FON project plates (the Golosiiv overlapping the northern sky) and the Astrographic Catalogue (Carte du Ciel) data is described briefly. The procedure of plate measurements with the PARSEC measuring machine as well as the methods of their reduction are considered. The results of comparing the FONAC 1.0 with other astrometric catalogues as well as description of the second version of the catalogue FONAC 2.0 are given. Value of the FONAC catalogue series on a background of the Post-Hipparcos astrometry is discussed.

## INTRODUCTION

Astrometry deals with the construction of spatial and temporal reference systems. During the 20th century the photographic astrometry technique was widely used for this purpose. Photographic observations were very fruitful at the middle of the last century. That is why photographic astrometry became one of main scientific directions of the new-born Golosiiv Observatory. For the space of five decades photographic observations were carried out systematically at this Observatory and some photographic catalogues were compiled.

In the middle of the 1970s the Main Astronomical Observatory (non-official name is the Golosiiv Observatory) initiated a project of photographic overlapping the sky by means of wide-angle astrographs available in the USSR. Necessity of new sky surveys has been widely discussed at that time. First of all it was necessary to obtain new epoch of observations. Besides that available reference frame needed in densification and extension to more faint objects. One can note some preconditions to these efforts:

– some soviet observatories were supplied with the same type wide-angle astrographs;
– well-known astronomer H. Eichhorn developed the method of overlapping plates;
– new AGK3 reference catalogue has appeared in 1975;
– there were rather reliable first epoch observations given with the Astrographic Catalogue (Carte du Ciel project);
– at last we had wide experience in the field of photographic astrometry at that time.

## FON PROJECT. PHOTOGRAPHIC OBSERVATIONS

The project of fourfold overlapping the northern hemisphere of sky known as FON (Fotografichny Ohlyad Neba – Photographic survey of the sky) was initiated by I. Kolchinsky and A. Onegina at the Golosiiv Observatory in 1977 [4]. It was supposed to carry out fourfold overlapping the northern sky by means of the same type C. Zeiss wide–angle astrographs. In 1982 six observatories of the former USSR started regular observations under the FON program. Here are these observatories: Abastumani (Georgia), Dushambe (Tajikistan), the Golosiiv Observatory (Ukraine), Kitab (Uzbekistan), the Kazan Station at Zelenchuk (Russia), Zvenigorod (Russia). All the astrographs have the same aperture ($D = 0.4$ m) and different focal lengths, namely $F = 2$ m (Dushambe, Golosiiv, Zelenchuk, Zvenigorod) and $F = 3$ m (Abastumani, Kitab). The working fields of the astrographs for all observatories were accepted identical and equal to $4^\circ \times 4^\circ$.

All observations were carried out according to uniform coordinated format. Six observatories were combined into four groups in order to ensure the fourfold overlapping the northern sky. Some characteristics of the FON project are shown in Table 1.

Between the groups the centres of plates were displaced for 2° in right ascension and/or declination. To consider magnitude equation there were two exposures of different duration (on the average 18 min and 40 s) on each plate, shifted in RA and DEC by about half a millimeter. The astrometric limiting magnitudes of star images for two exposures on the plates with ORWO ZU-21 emulsion were equal to $B = (15 - 16)^m$ and $B = (12 - 13)^m$, respectively.

Table 1. Some characteristics of the FON project

| Overlap | Station | Latitude | Dec from | Dec to | Plates required | Plates obtained |
|---|---|---|---|---|---|---|
| 1 | Golosiiv (Ukraine) | 50° 27′ | +32° | +90° | 952 | ~ 2300 |
| | Kitab (Uzbekistan) | 41° 45′ | −4° | +32° | 900 | ~ 500 |
| 2 | Zelenchuk (Russia) | 43° 47′ | −6° | +90° | 1783 | 1783 |
| 3 | Abastumani (Georgia) | 41° 35′ | −6° | +30° | 900 | ~ 900 |
| | Zvenigorod (Russia) | 55° 45′ | +30° | +90° | 973 | 973 |
| 4 | Dushambe (Tajikistan) | 38° 33′ | −4° | +90° | 1762 | ~ 1370 |

The coordination of observations under the FON program was broken as a result of the USSR disintegration. As one can see from Table 1, Dushambe and especially Kitab could not carry out observations completely. That is why at the Golosiiv Observatory were obtained negatives for the whole northern sky including Kitab overlapping zone. More than 2300 plates were taken.

In parallel with observations the methodical researches were carried out in order to increase accuracy of determination of coordinates and proper motions of stars. In particular, special series of measurements by means of semi-automatic measuring machine "Ascorecord" were carried out for investigation of random and systematic errors (like a coma, magnitude equation and distortion) in determination of star positions from observations at the Golosiiv Observatory wide-angle astrograph. In 1995 observations were finished and we began measuring the plates.

## MEASUREMENTS

It was decided to apply the FON photographic collection to the determination of positions and proper motions of all stars in the Astrographic Catalogue (AC) which is the product of well–known international photographic enterprise "Carte du Ciel". Photographic observations started in 1891 within the project were finished only in the early 1950s. At present, some versions of the AC are available. The most generally used of them are the AC2000 and AC2000.2 [7] which consist of positions of 4 millions of stars up to $14^m$ on the whole sky based on the new reduction of measured coordinates to the Hipparcos catalogue system. We used the AC2000 in two ways: (i) as the input catalogue for automatic measuring machine, and (ii) as the first epoch of observations for determination of stars' proper motions.

About 1600 the best Golosiiv plates were selected for measurements. In addition, 90 Kitab plates for equatorial zone were used as well. Measurements of such plenty of negatives were made by means of automatic measuring machine PARSEC (Programming Automatic Radial-Scanning Coordinatometer). The device consist of an optical-mechanical part KOMESS, electronic-recording block and microcomputer. Four such complexes were installed at the Golosiiv, Nikolaev and Pulkovo observatories as well as at the Sternberg Astronomical Institute in Moscow. The complex can work in a mode of automatic measurement of the images on astronegatives under the given list of stars. Operator can also choose objects of measurement independently with the further automatic registration of coordinates. Depending on accuracy of input coordinates of stars PARSEC measures automatically from 400 up to 900 images per hour.

The carried out researches have shown that PARSEC provides more accurate and homogeneous (depending on diameters of star images) measurements than executed manually on measuring device "Ascorecord". The random errors of coordinate measurements by means of PARSEC are on average ±2.8 microns for a long exposures and ±2.1 microns for a short ones.

All the plates were measured by means of Kyiv PARSEC. About 80 astronegatives were repeatedly measured on the same device at the Nikolaev Observatory for estimation of measurement quality.

## PLATE ADJUSTMENT

All the plate measurements were reduced twice. Firstly the PPM catalogue was used as the reference system which gave us about 100 reference stars on the working field 4°×4°. Plate parameters were obtained from joint solutions of connection equations for both exposures to eliminate of coma and magnitude equation effects. These solutions were carried out using the Gramm–Schmidt orthogonalization method. The statistical $F$-criterion was used for estimation of significant terms number in the reduction models. Later on, after appearance of two catalogues: (i) AC2000 (positions of star of all AC zones in the Hipparcos system) and (ii) ACT (combined data of both AC2000 and Tycho catalogues), new reduction of the FON project plates was carried out. The ACT catalogue was used as the reference one and the AC2000 data were used as the first observation epochs. By the way average epoch of the ACT catalogue (1991.25) is closer to average epoch of the Golosiiv part of the FON program (1989.19) rather than of the catalogue PPM, which average epoch is close to 1931.0. Therefore, new reduction of the measured coordinates using the catalogue ACT as reference one was carried out [9]. The reduction was individually made for each exposures. The average random errors of weight unit are equal to ±2.5, ±3.0 microns (for long and short exposures, respectively). Proper motions of stars were obtained from comparison of their reduced coordinates with the same ones taken from the AC2000 catalogue. For correction of a residual aberrations the method of masks was used. The masks were constructed from analysis of differences of star positions given in the Guide Star Catalogue (GSC) and FON data in individual intervals of star magnitudes (see Fig. 1).

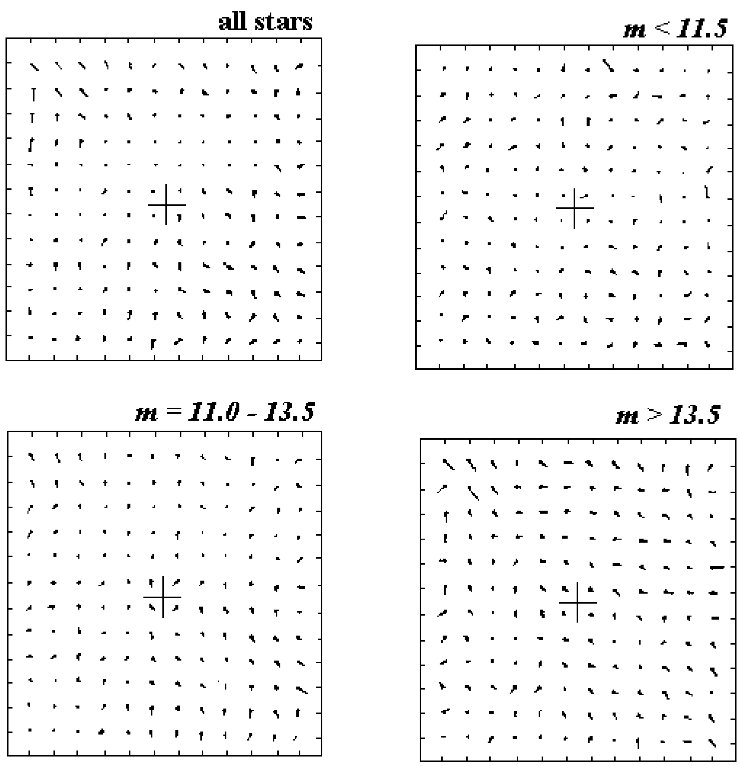


Figure 1. The plate masks of the Golosiiv wide-angle astrograph (working field is equal to $4^\circ \times 4^\circ$, width of cross is equal to $2''$)

The aberration masks for the Golosiiv wide-angle astrograph (GWA) were used for taking into account the errors of measured coordinates depending on positions and magnitudes (mainly, like coma and magnitude equation). Besides that the aberration masks for the Palomar Schmidt Telescope were constructed as well from comparison of the FON and GSC data (see Fig. 2).

These masks are in a good coincidence with those constructed by other independent investigators. One can see that aberration pattern is more complicated for the Palomar Schmidt Telescope than in the case of GWA.

## PHOTOMETRY

Determination of photometric characteristics of stars was the next step. Using the automatic measuring machine PARSEC the diameters ($D$) of star images on each plate were measured. Photometric data taken from the catalogue ACT were used for the final calibration of the measured machine magnitudes of stars and determination of $B_J$-magnitudes of stars in the Johnson photometric system. Colour indexes $(B-V)$ were obtained using the $V$-magnitudes from the GSC1.1 catalogue reduced to the Johnson system $(V)$. In the same way $R$-magnitudes, given in the USNO-A2.0 catalogue, were applied to obtain the colour indexes $(B-R)$ of stars.

## COMPILING THE FONAC 1.0 CATALOGUE

As a result of processing the measured data we obtained about 1700 separate files with calculated positions, proper motions and photometric characteristics of stars for each FON project plate. Taking into account that there were two exposures on plates, and some plates contained overlapping working fields, the part of stars had several coordinates and photometry determinations on different epoch of observations. Therefore, all the star data were reduced to general epoch J2000.0 and the final catalogue was obtained as mean-weighted of all determinations. The final catalogue was called FONAC (FON+AC) [3]. That is a combination of the FON and AC data. The first version of the FONAC catalogue consists of positions, proper motions and $B_J$-magnitudes for 2 004 701 stars of the Astrographic Catalogue list, including the $(B-V)_J$-magnitudes for 1 712 420 stars and $(B-R)_J$-values for 1 779 442 stars in 93 one-grade zones of declinations (from $-2°$ to $+90°$). The mean epoch of catalogue is 1988.19. Mean precision of the catalogue for stars brighter than $10^m$ is $\pm 0.2''$, $\pm 0.003''$/yr and $\pm 0.18^m$ in positions, proper motions and magnitudes of stars, respectively. The errors are increasing for more bright and more faint stars.

The FONAC 1.0 catalogue [3] is available on the Main Astronomical Observatory of the NAS of Ukraine home page [ftp://ftp.mao.kiev.ua/pub/astro/fonac]. It was transferred to the Strasbourg Centre of Stars Data [http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=I/261] and was distributed on CD-discs.

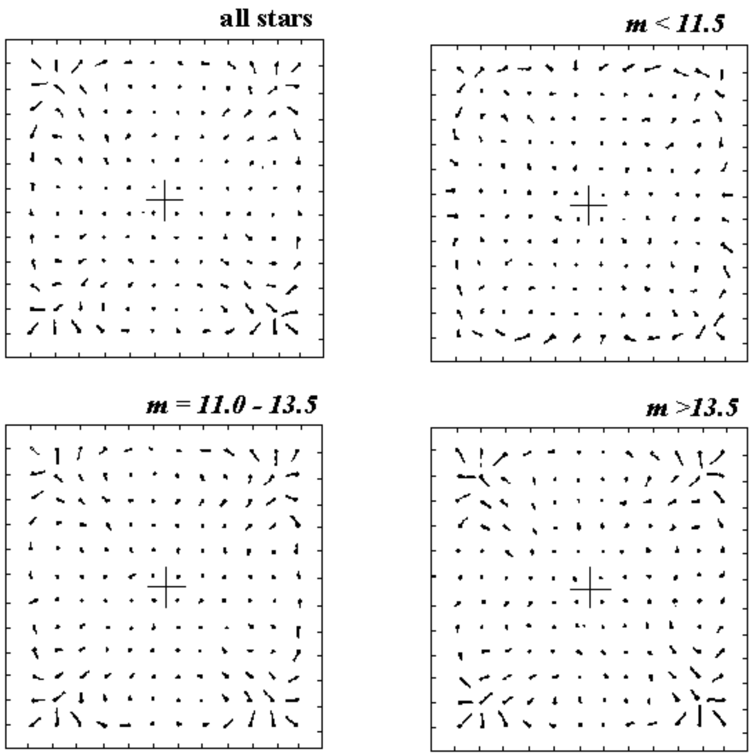


Figure 2. The plate masks of the Palomar Schmidt Telescope (working field is equal to $6.5° \times 6.5°$, width of cross is equal to $2''$)

## CATALOGUE COMPARISON

The FONAC catalogue having been compiled, the appropriate control of accuracy of the obtained results was carried out at each stage of processing the measurements. However, all derived estimates of errors basically characterized only internal accuracy of the catalogue. For investigation of real accuracy there was necessary a comparison with other independent sources which would have high accuracy of the data on epoch close to average epoch of our catalogue and for all range of star magnitudes [10].

Positions and proper motions of stars given in the FONAC catalogue were compared to the high-precision catalogues: space-born Hipparcos (error of positions and proper motions are $\pm 0.001''$ and $\pm 0.001''$/yr, respectively) and ground-based CMC11 ($\pm 0.06''$ and $\pm 0.004''$/yr). 41 759 stars were selected from the Hipparcos catalogue and 66783 stars – from the catalogue CMC11 after their identification. Systematic differences $\Delta_i$ between these catalogues were represented by a series development using product of Hermite $H_p(y(m))$ and Legendre $L_n(x(\delta))$ polynomials as well as the Fourier $F_{kl}(\alpha)$ terms depending on equatorial coordinates ($\alpha_i$, $\delta_i$) and brightness ($m_i$) as [6]:

$$\Delta_i = \sum_{j=1}^{g} Y_j(\alpha_i, \delta_i, m_i) b_j \,, \tag{1}$$

$$Y_j = R_{pnk}\, H_p(y(m))\, L_n(x(\delta))\, F_{kl}(\alpha) \,, \tag{2}$$

where $b_j$ are unknown coefficients of the development series. At comparison we were limited to the terms of the first order of developments which depend on magnitude and terms of the second order – from coordinates. Thus, the maximum quantity of the terms of developments was accepted equal to 30. Significant (at 1% level of significance) coefficients $b_j$ of developments for differences (FONAC–Hipparcos) are given in Table 2.

Table 2. Some terms of development of differences (FONAC−Hipparcos)

| $j$ | $p$ | $n$ | $k$ | $l$ | For $\Delta\alpha\cos\delta$ (0.001″) | For $\Delta\delta$ (0.001″) | For $\Delta\mu_\alpha\cos\delta$ (0.001″/yr) | For $\Delta\mu_\delta$ (0.001″/yr) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | $-3.9 \pm 0.9$ | $-4.0 \pm 1.0$ | – | $0.01 \pm 0.002$ |
| 3 | 0 | 0 | 1 | 1 | – | – | $-0.07 \pm 0.02$ | – |
| 16 | 1 | 0 | 0 | 0 | $-2.5 \pm 0.9$ | – | $-0.06 \pm 0.02$ | – |
| 17 | 1 | 0 | 1 | –1 | – | – | $0.10 \pm 0.02$ | – |
| 18 | 1 | 0 | 1 | 1 | – | – | $0.06 \pm 0.02$ | $0.06 \pm 0.02$ |
| 20 | 1 | 0 | 2 | 1 | – | – | – | $-0.05 \pm 0.02$ |
| 23 | 1 | 1 | 1 | 1 | – | $-3.0 \pm 1.0$ | – | – |
| 30 | 0 | 0 | 1 | 1 | – | – | $-0.06 \pm 0.02$ | – |

The mean square differences of coordinates for all stars in FONAC–Hipparcos comparison are approximately $\pm 0.004''$ in both coordinates, and $\pm 0.0001''$/yr for proper motions of stars. Taking into account these systematic differences we practically do not change the square differences of coordinates and proper motions of stars which are $\pm 0.18''$ and $\pm 0.19''$ for coordinates $\alpha$ and $\delta$, respectively, and equal $\pm 0.0037''$/yr on average for the proper motions of stars.

The mean square differences of coordinates and proper motions in (FONAC–CMC11) after considering the significant coefficients of developments are on average $\pm 0.24''$ for positions and $\pm 0.005''$/yr for proper motions in both coordinates. The same estimates for the differences (Hipparcos–CMC11) are equal to $\pm 0.1''$ and $\pm 0.0037''$/yr, respectively. If considering the errors of CMC11 catalogues in the mean square differences (FONAC–CMC11), we obtain the same values for the accuracy of FONAC catalogue that in the case of comparison to the Hipparcos catalogue (namely: $\pm 0.2''$ and $\pm 0.004''$/yr for positions and proper motions, respectively).

Dependencies of random errors of the FONAC catalogue from star magnitudes were obtained from comparison between the specified catalogues in individual intervals of star magnitudes (see Fig. 3). One can see that for stars brighter $6^m$ and fainter $14^m$ these errors increase up to $\pm 0.3''$ and $\pm 0.006''$/yr for positions and proper motions, respectively.

## GALAXY KINEMATICS

The FONAC data were used to determine some kinematic parameters of the Milky Way, in particular the Oort constants, direction of solar apex, secular parallaxes as well as galactic rotation. The most general Ogorodnikov–Milne model [5] was chosen for this purpose. This model, which considers the solar motion, differential rotation and space deformation of the Galaxy, was applied to the FONAC catalogue stars in three bands with different colour indexes $(B-V)$ and proper motions $(\mu_\alpha \cos\delta, \mu_\delta) \leq 0.05''$/yr, namely: $(B-V) < 0.5^m$, $0.5^m < (B-V) < 1.0^m$, $(B-V) > 1.0^m$. The following parameters have been estimated: $P = M_{12}$, $Q = W_{21}$ are the Oort's constants; $C = 0.5(M_{11} - M_{22})$, $K = 0.5(M_{11} + M_{22}) - M_{33}$, $N = M_{13} + W_{13}$, $D = W_{32} - M_{23}$, $L = W_{13} - M_{13}$, $R = W_{32} + M_{32}$ are the parameters, describing rotation and space deformation of the Galaxy (here $M_{ij}$ are elements of the rotation matrix in the Ogorodnikov–Milne theory). The most significant kinematic parameters are given in Table 3 (in $0.0001''$/yr). These values are obtained rather reliable. The rest of parameters, which describe rotation and deformation in the planes $XZ$ and $YZ$, are very small and not always reliable, besides the parameter $W_{13} = -6 \pm 1$ (describing rotation in the $XZ$ plane), which is reliably obtained.

Our results are in a good coincidence with the data obtained by V. Vityazev [8] and V. Bobylev [1] from analysis of stars' proper motions in the Hipparcos catalogue. The direction of solar apex obtained from the FONAC and Hipparcos data are in a good coincidence as well.

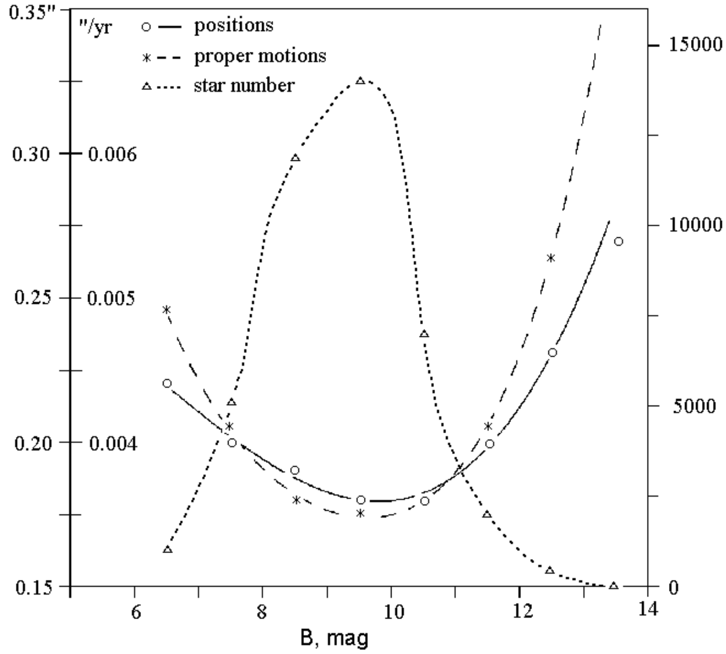


Figure 3. Dependences of random errors of the FONAC catalogue from star FONAC 1.0 found from comparison to the Hipparcos catalogue

**NEW VERSION OF THE CATALOGUE (FONAC 2.0)**

At the beginning of 2000 new version of the Tycho catalogue (Tycho-2) [2] had appeared which consists of nearly in 2.5 times more stars and has considerably more precise positions and proper motions than its predecessor Tycho-1. A little later there was accessible a catalogue AC2000.2 [7], made on the basis of a new reduction of the AC plates and with star magnitudes specified from the Tycho-2 catalogue. Therefore, there was an opportunity to use the new reference catalogue to improving an accuracy of reduction of the measured coordinates in particular to exclude magnitude equation errors.

Indeed, the accuracy of determination of plate constants was considerably improved. The corresponding root-mean-square errors had been decreased almost twice. However, an accuracy of new equatorial coordinates and proper motions of stars did not differ from those found in the first FONAC catalogue version. That is why

Table 3. Kinematic parameters obtained from analysis of the FONAC and Hipparcos catalogue data (in 0.0001″/yr)

| Parameters | FONAC [11] | Hipparcos Vityazev [8] | Hipparcos Bobylev [1] |
|---|---|---|---|
| $Q$ | $-25 \pm 1$ | $-25 \pm 3$ | $-27.0 \pm 0.8$ |
| $P$ | $+26 \pm 1$ | $+29 \pm 4$ | $+24.3 \pm 1.1$ |
| $C$ | $-14 \pm 1$ | – | – |
| $K$ | $-11 \pm 2$ | – | – |
| $W_{13}$ | $-6 \pm 1$ | $-5 \pm 3$ | $-3.6 \pm 1.5$ |
| $W_{23}$ | $+2 \pm 1$ | $-1 \pm 3$ | – |
| $M_{13}$ | – | $+2 \pm 4$ | – |
| $M_{23}$ | $-2 \pm 1$ | $-2 \pm 3$ | – |
| | SOLAR | APEX | |
| $l$ | $+64.0° \pm 0.5°$ | $+61.0° \pm 0.3°$ | – |
| $b$ | $+19.0° \pm 0.5°$ | $+11.0° \pm 0.3°$ | – |
| The number of stars | 910 395 | 113 710 | – |

we conclude that the version FONAC 2.0 is the limit of increasing the catalogue accuracy owing to use both new reduction models and new reference catalogue.

**FUTURE PROSPECTS**

Is there a future for the FON project? And what kind is this future? As one could understand we extracted astrometrical information only concerning to stars of 12th or 13th magnitudes from one photographic overlapping the sky. The FONAC catalogue we consider as a pilot product of the FON project. Theoretically we have possibility to improve and extend of the FONAC data up to stars of 15–16 magnitudes in two ways: (i) by re-measuring the Golosiiv FON plates and (ii) by measuring the plates obtained within other three overlapping the northern sky (Abastumani+Zvenigorod, Dushambe and Zelenchuk) in order to use completely the advantages of a method of fourfold overlapping the sky. It would enable us to increase accuracy of star positions approximately twice.

However, there are some difficulties with measurements of such plenty of material, because measuring machines like PARSEC are obsolete both morally and physically. Thus, we study now a possibility of plate measurements by means of scanners. In particular, five FON plates were tested using scanner Microtek ScanMaker which resolution is equal to $900 \times 900$ pixels on inch. The rectangular coordinates and photometric characteristics of stars were obtained using a program complex MIDAS/ROMAFOT. The reductions of rectangular coordinates were carried out with the Tycho-2 catalogue as the reference one. After corrections of rectangular coordinates of stars for systematic errors of the scanner ($\pm 3$ mkm on $x$ and $\pm 21$ mkm on $y$) and averaging the results of several scans the final errors of determination of positions and photometry consist of about $\pm(2–3)$ mkm ($0.2''$) and $\pm 0.2^m$, respectively.

Hence, it is possible to achieve accuracy of a measuring device like PARSEC scanning the plates by means of qualitative enough scanners. It gives us a hope to increase an accuracy of star positions approximately twice after full realization of the FON project possibilities. It is also supposed that in some time the FON data will be used as the first epoch of observations for CCD-surveys of the sky.

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