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FON: FROM START TO FINISH

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ABSTRACT. Almost 40-year history of FON project ended with the creation of the whole northern sky catalog of objects down to B $\leq$16.5^m. The idea of 4-fold overlapping of the northern sky with 6 wide-field astrographs has not been realized in full. For historical reasons it has been transformed into the 2-fold overlapping observational program of MAO NAS of Ukraine, resulted in three versions of the multimillion catalog of positions, proper motions, and B-magnitudes of stars. The first version of 1.2 million stars had been finished before the 2000s and is based on the AC object list. The measurements of plates were made by automatic measuring complex PARSEC, specially developed for massive photographic reviews. As the input list was limited by AC objects, the most part of stars on the FON plates remained unmeasured. Principles of workflow organization of such works formed the basis for the further development of the project using the latest IT-technologies. For the creation of the second and the third versions of the catalog, the list of objects was obtained as a result of total digitizing of plates and their image processing. The final third version contains 19.5 million stars and galaxies with the maximum possible for the photographic astrometry accuracy. The collection of plates, obtained in other observatories – participants of the project, are partially safe and can be used for the same astrometric tasks.

Keywords: virtual observatory tools – astrometry – techniques: photometric – methods: data analysis – catalogs

1. Introduction

The plan of the photographic review of the northern sky (FON) was proposed in 1976 at MAO NAS of Ukraine by astronomers I.G.Kolchinsky and A.B.Onegina [Kolchinsky, 1977]. The idea arose after the acquisition of similar wide-angle astrographs of Carl Zeiss company with focal length 2 or 3 meters and aperture 40 cm in several observatories of the former USSR. For that moment, the Carte du Ciel project (CdC) was entirely completed. That project launched as far back as the end of XIX century and resulted in the compiled catalog of precise positions of stars down to 11^m and the photographic atlas of stars down to 14^m made by photographic plates of zone astrographs. The digitizing of CdC plates, made at Sternberg astronomical institute in Moscow in 80-s of the last century, ended with the creation on their basis the Astrographic Catalogue (AC), containing 4 million stars at the epoch of observations and equinox B 1950.0. It was in the air, the idea of repetition of that project using modern instruments. The epoch difference for over 70 years provided the proper motions of a vast amount of stars with the best accuracy for that moment. It was possible on condition that the observational program, plate measurements and their treatment would be completed quickly.

The first condition was provided by similar instruments able to obtain the necessary photographic material during several years. After the thorough testing of instruments, the optimal overlapping scheme was proposed, and the common technique of observations was agreed [Kislyuk, 2000]. The optimal working field was accepted to be 4^0x4^0 for all astrographs. In order to account the magnitude equation, the observations were carried out with two exposures of different duration with the shift of the tube between them along both coordinates. The short expositions are 18-22 seconds long, and the long one is 16-24 minutes.

The second condition of a successful project should be to develop and devise the automatic facilities for measurements of plates. A.V.Sergeev and O.E.Shornikov, engineers (for that moment) of Kazan Engelhardt observatory created the programming automatic measuring complex PARSEC designed for massive star measurements [Sergeev, 1991]**.** Five PARSEC complexes were installed in Nikolayev, Kiev, St.Petersburg (Pulkovo), Moscow (Zvenigorod), Kazan. Two of them (Kiev and Nikolayev) were involved into FON project.

PARSEC was able to measure the rectangular coordinates of star images with a repeatability $\pm$0.6 – 2 μm in dependence on the quality of images and stellar magnitudes with an accuracy $\pm$0.01 – 0.02^m. It had two modes of operation. The first one is the automatic scanning of all objects presented in the given area. The second mode was semi-automatic scanning the sample of objects with precalculated coordinates. This mode was used for the measurement procedure in FON project as the task was to obtain proper motions of stars. The number of objects measured per hour was 400 to 900 in dependence on precalculated coordinates' accuracy.

For the implementation of the third condition the starting point was the method of the processing the pool of the overlapped plates as the whole, using variables describing the common plate parameters together with individual ones. The method was mathematically developed and proved by H.Eichhorn [Eichhorn, 1963]**.** The solution of

the system of equations with tens of thousands of variables, as it was shown by H.Eichhorn, supposed to be the best way to account the instrumental aberrations and provide the homogeneous accuracy of the resulted catalog, obtained on the basis of the pool of overlapping plates. The main problem of the method was that the computing facilities, available at the time, were not able to execute that task entirely for such a system of equations. Therefore, in FON project the Eichhorn method was decided to apply partially, using the benefits of the overlapping without solving the joint bulky and often ill-conditioned systems of equations.

The FON project was supposed to provide the four-fold overlapping of the northern sky by several similar telescopes. Each observatory participating in the project had to carry out the one-fold covering of its part of the northern hemisphere with the shift of plate centers by 2^o relative to other observatories in order to eventually obtain the four-fold overlapping. After the collapse of the USSR, the coordination of work was broken and some observatories could not complete their observations. On the same reason, the measurements of plates could not be conducted in most observatories. Therefore, the decision was made to enhance the MAO NASU observational program to the whole northern hemisphere including the most southern Kitab zone.

The regular observations started in 1982. During 15 years of observations (1980-1995) in MAO NASU, it was obtained near 2400 plates covering the sky from $+2^o$ to $+90^o$ on declination. Another 90 plates in -2^o to $+2^o$ declination zone were received from Kitab observatory.

2. FONAC V1.0

The first version of the catalog was built on the basis of 1700 plates of best quality selected for measurements on MAO NASU PARSEC complex. Some of the plates were repeatedly measured in Nikolayev observatory to evaluate the accuracy of measurements. The input catalog for the measurements was AC. To ensure the stability of metrological characteristics of the measuring complex during the measurements the algorithms and programs for control and diagnostic of PARSEC equipment were devised and implemented. They provided the continuous monitoring of repeatability of measurements, the current analysis and registration of non-standard situations that arose in measuring process and during the preparation of input files for their further treatment. The time of measuring of one plate with the mean rate of 600 objects per hour varied from 1 and a half to 20 hours relatively to the number of stars fixed on the plate. All the measurements were carried out during 1991-1998.

For the optimization of the measurements and systematization of the accumulated data, the database with the control software was developed and implemented. The user interface allowed to create, replenish and correct the database of measured plates, to make a schedule of the measurements, to obtain the reference data about measured plates, to control the measurement process, to compose reports on measured declination zones, to prepare input files, to make the technical monitoring of measurement process and so on. The input files for measurements include lists of previously calculated rectangular coordinates of objects, corrected for the distortion and coma effects. Lists were divided into blocks of 400 objects. Four control stars were measured at the start and the end of each block for the accounting of the instrument parameters' variations. Both expositions were measured for bright stars. For stars fainter than 10.5^m only long exposition was taken into account. The software package includes Assembler, FORTRAN, and Pascal modules.

The initial reduction of measured coordinates was made with PPM star catalog as a reference. The reduction models were used in the form of incomplete cubic polynomials for each coordinate separately. Plate parameters were derived from the combined solution of connection equations for both exposures. To evaluate the number of significant members in the reduction model, the solution of conditional equations was made by Gram-Schmidt orthogonalization method. The errors of measurements, depending on brightness and a star position on a plate were accounted by constructing the aberration masks using data of GSC1.0. After the completion of HIPPARCOS mission catalogs and their derivative ones the re-reduction of measurements became possible. As a result, it ultimately gave the improvement of the accuracy ofn positions and proper motions of one and a half times. [Yatsenko, 2000]. The photometric reduction into B system was made using Tycho and USNO A2.0 catalogs. B-V color indices were obtained from Tycho and GSC 1.1 data.

The final reduction of measured coordinates was made with ACT catalog as a reference. ACT is based on data of AC2000, which is AC in the HIPPARCOS system, and Tycho. The result of final reduction was FONAC, the catalog of positions and proper motions based on the data of FON project and Astrographic Catalog [Kislyuk, 2000]**.** The first version of FONAC contains positions, proper motions and photometric data in *B, B – V, B – R* bands for 2 004 701 stars from AC list in the declination zone from -2° to +90°. The mean epoch of positions is 1988.19. For the determination of proper motions, AC2000 data was used as the first epoch. Photometric values of stars were derived from data of ACT, GSC 1.1, USNO A2.0. The accuracy of FONAC in dependence on object brightness is evaluated as ±0.18-0.25" for positions, ±3-5*mas/yr* for proper motions and $\pm 0.18\text{-}0.25^m$ for brightness. As a rule, errors increase for stars brighter than 7.5^m and fainter than 11.5^m.

The main shortcoming of the first FONAC version was that it is created on the basis of the one-fold covering of the sky instead of the four-fold overlapping. In addition, the abilities of PARSEC measuring complex were limited by an AC input catalog data list. Limited magnitudes in it are $\pm 13\text{-}13.5^m$ in B band. Therefore, after the completion of the first version, the most part of stars on the FON plates remained unmeasured ($\sim 13.5\text{-}16.5^m$) .

3. Ukrainian Virtual Observatory and new prospects of FON

In the 1990s, when the world has begun implementation of the ideas of digital astronomy, the IVOA (International Virtual Observatory Alliance) working group and IAU initiated the compilation of the catalogue of archives of astronegatives (Catalogue of Wide-

Field Plate Archives, http://www.skyarchive.org/catalogue.html, WFPDB – the archive of wide-angle photographic glass libraries) on data of ~200 astronomical institutions of the world. Those data had to be prepared in accordance with formats of data presentation devised by this group with the aim of their digitizing. The established database, obtained during the FON project workflow, became the basis for MAO WFPDB-archive creation and its inclusion into the global database of observations being a part of UkrVO Joint Digital Archive [Vavilova, 2012a, Vavilova, 2012b]. The development of information technologies and the upgrade of computer facilities make possible the complete digitizing of FON plates, their processing and data mining of all objects fixed on them.

In the early 2000s, it has started the mass digitization of negatives using flatbed scanners equipped with transparency module for digitizing of transparent media. The preceding thorough investigations of scanner digitizing capabilities, have shown that in the case of proper methods of scanning [Andruk, 2012, Protsyuk, 2014a, Protsyuk, 2014b] and development of the appropriate software [Andruk, 2014, Andruk, 2015a, Andruk2015b, Protsyuk, 2014a, Protsyuk, 2014b, Protsyuk, 2015, Kazantseva, 2015, Muminov, 2016, Vavilova, 2014, Yizhakevych, 2014 Yizhakevych, 2015 Yizhakevych, 2016, Yizhakevych, 2017] the feasibility exists to obtain coordinates and brightness of objects with the best accuracy possible for the photographic material. Two models of scanners were selected for FON plates digitizing, namely Microtek ScanMaker 9800XL TMA and Epson Expression 10000XL [Andruk, 2005a, Andruk, 2007, Andruk, 2010, Golovnya, 2010, Yatsenko, 2011]. The initial variant of plate image processing supposed to use two frames of each plate turned one to another by 90° with the aim of excluding the scanner errors along the axis of the matrix movement direction. That variant significantly increased the time consuming and the volumes of data storage. The preliminary version of FON comprehensive catalog included 15 million objects, was made using that method [Yatsenko, 2016].

4. The final version of FONAC

When processing digital images the improved algorithms of primary treatment and the reduction were developed. They allowed to reject the technique of two frames and to eliminate the errors of scanning completely in the processing of one direct scan without prejudice to the final accuracy. Moreover, these algorithms made it possible to use the total field of the plate, that provides at least a 2-fold overlapping for 90% of objects and to exclude the images of the short exposure from the final processing. The software for plate image processing and the reduction of the measured coordinates and stellar magnitudes [Andruk, 2005, Andruk, 2015,] has been developed on the basis of the standard MIDAS/ROMAFOT modules for the CCD images and supplemented with the special modules. The last ones implemented the algorithms of the treatment of broad star fields, the correction of scanner errors and the image geometry influence on a position of an object using the reference catalog data by successive approximation (3-4 steps). The application of the above said algorithms for the correction of primary data reduced the reduction errors more than two times compared to non-corrected values and gave an average of 20% better the final accuracy in comparison with the two frames technology.

The final version of FONAC is based on the digital images of 2260 plates of Kiev and Kitab declination zones on which 153 million objects of various nature were registered. The catalog includes 19 568 347 stars and galaxies down to B $\leq 16.5^m$ at the epoch 1988.1 [Andruk, 2016a, Andruk 2016b]. Each object was in an average obtained on 4 plates. 1,8 million entries in the catalog have only one image. Plate images were obtained in grey 16-bit color range with the resolution 1200 dpi. The astrometric reduction was made in the reference system of Tycho-2 at the epoch of plate expositions. The photometric reduction was carried out into the B – band of the system of photoelectric standards [Andruk, 1995, Andruk, 1996, Mermilliod, 1991, Kornilov, 1991, Relke, 2015]. In the overlapping areas positions and stellar magnitudes were obtained as a weighted average based on the weights derived for each object from the reduction of the individual plates. The convergence between obtained coordinates of objects and Tycho-2 values is $\sigma_{\alpha\delta} = \pm 0.06"$, the convergence with photoelectric B-values is $\sigma_B = \pm 0.15^m$. The comparison of the catalog with UCAC-4 shows the rms differences $\sigma_{\alpha\delta} = \pm 0.30"$. The final version of the catalog is supplemented by proper motions and stellar magnitudes f, B, V, r, i from UCAC-4 [Zacharias, 2013].

5. Conclusion

Almost 40-year history of FON project ended with the creation of the whole northern sky catalog of objects down to B $\leq 16.5^m$. In the astrometry of the former USSR FON has become the only project of massive star catalogs from observations to catalog compilation and, from the very start to the finish made of the same team of participants. Unfortunately, the realities of life have not allowed implementing in full-scale the idea of I.Kolchinsky and A.Onegina of 4-fold sky overlapping by instruments of 6 observatories. In the final stage of the project, we used the plates of two observatories: Kiev and partially Kitab as well as several plates of Zelenchuk collection. The destiny of Abastumani and Zelechuk collections is unknown. The collection of Zvenigorod in its time was measured using the Moscow PARSEC complex and resulted in FOKAT stellar catalog. Now it is included in the database of Zvenigorod WFPDB-archive and is used for the solution of various special tasks where the time series of observations are required. The Dushanbe collection is safe and can be used for astrometric tasks. The Kitab collection is now being actively digitized and also used for the solution of various astrometric research tasks [Muminov, 2013, Muminov, 2014, Muminov, 2016a]. The FON project is unique with different standpoints, including the organization of mass measurements of astronomical photographic material containing millions of objects. The creation of automatic measuring complex required enormous technical and programming preparatory work starting from the selection of available stellar catalogs and assession of their applicability to serve as input list of objects to the development of the hardware and software for general control of the process. Henceforward, the elaborated and practically tested principles of the massive meas-

urements organization became the cornerstone of the UkrVO archive databases and the system of their administration [Pakuliak, 2012], which, in turn, made it possible to return and raise the FON project at the state-of-the-art level.

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