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WIDE-FIELD PLATES OBSERVATIONS OF STARS FROM EARTH ORIENTATION CATALOGS (EOC)

YAVOR CHAPANOV[1], KATYA TSVETKOVA[2], MILCHO TSVETKOV[3], JAN VONDRÁK[4], CYRIL RON[4], VOJTĚCH ŠTEFKA[4]

[1]*National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, Acad. G. Bonchev Bl.3, 1113 Sofia, Bulgaria*
E-mail: chapanov@clg.bas.bg
[2]*Institute of Mathematics and Informatics Bulgarian Academy of Sciences, Acad. G. Bonchev Str. Block 8, 1113 Sofia, Bulgaria*
E-mail: katya@skyarchive.org
[2]*Institute of Astronomy, Bulgarian Academy of Sciences, Tzarigradsko shose Blv. 1784, Sofia, Bulgaria*
E-mail: milcho@skyarchive.org
[4]*Astronomical Institute, Academy of Sciences of the Czech Rep., v.v.i. Boční II, 141 31 Prague 4, Czech Republic*
E-mail: vondrak@ig.cas.cz, ron@ig.cas.cz, stefka@ig.cas.cz

Abstract. The Earth Orientation Catalogues (EOCs) are primarily meant to provide stable celestial reference frame in optical wavelengths for deriving Earth Orientation Parameters (EOP) from astrometric observations. The EOCs combine catalogues ARIHIP and TYCHO-2 with the rich observation material (variations of Latitude/Universal Time), obtained during the 20th century in programs of monitoring Earth orientation. Other possible source of information for improving the EOCs is the WFPDB (Wide-Field Plate Database). The number of plates, containing EOCs stars and their distribution in time are determined by means of the search engine of the WFPDB.

1. INTRODUCTION

A significant part of the scientific investigations in the field of geosciences is directly connected with astrometrical observations and star catalogues. Namely the sections of geosciences, which determine the Earth orientation in the space with respect to the Celestial Reference Frame: geodesy, geophysics, geodynamics, etc., are involved. The optical astrometry and the astrometrical observations are useful to study decadal variations of the Earth rotation and gravity. The long-term

oscillations of the verticals, determined from universal time and latitude data in the 20th century, are useful for study of the local and regional gravity changes and their interconnections with some natural phenomena. The combination of optical astrometry data with modern space-based observational techniques, such as VLBI, GPS and SLR significantly expands the possibility of long-term analysis of Earth rotation and gravity.

The astrometrical observations of geographic latitude and universal time were a unique source of information of Earth orientation during the most of the last century. Nowadays the astrometrical observations from the period 1899-1992 are the only centenary series, used for determination of the variations of the local plumb-lines and Earth rotation and give us unique possibility of searching causality between these variations and global changes of the environment, climate, solar activity, ice melting and post-glacial rebound, mean sea level arising, earthquakes etc. Necessary precondition of successful utilization of the astrometrical observations in the field of modern scientific investigations is the improvement of the accuracy of star catalogues, where the proper motion of the stars (or their annual velocity on the celestial sphere) is a critical parameter. The determination of the proper motions with sufficient accuracy requires all star observations from the early epochs. The modern space observational campaigns that provide very accurate star positions are too short to allow estimation of the proper motions valid in a century spans. In this sense the accuracy increase of the proper motions is possible by using all possible star observations from the last century, which will facilitate the investigation of the decadal variations of the Earth gravity and rotation and their interconnection with some natural phenomena.

The optical astrometry data consist of more than 4 millions observations, collected from 33 observatories and the longest latitudinal series are from the observatories Carloforte, Gaithersburg, Kitab, Mizusawa, Ukiah, Pulkovo and Washington. The reliable astronomical observations have some advantages: they are directly connected with the Earth orientation parameters and gravity; they form a unique source of observations in the last 4 century, which is suitable for long-term analysis. The disadvantages of observations before 1992 from the optical astrometry are: less observations in the past, not suitable for short-term analysis and significant systematic errors in old star catalogues. The last disadvantage means that the successful use of optical astrometry data leads to necessity of improved star catalogues.

Nowadays we have four solutions for Earth Orientation Catalogs (EOC): EOC-1, 2, 3, 4 and six solutions for Earth Orientation Parameters (EOP): OA97, OA99, OA00, OA04, OA07 and OA10. Many observatories create their own individual solutions of star catalogues, for example - observatories Plana (Chapanov, 1998) and Ondřejov (Ron and Vondrák, 2003).

2. EARTH ORIENTATION CATALOGS IMPROVEMENT

The Earth Orientation Catalogs (EOC) are primarily meant to provide stable celestial reference frame in optical wavelength for deriving Earth Orientation Parameters (EOP) from astrometric observations. The general ideas of constructing these catalogs were outlined by Vondrák and Ron (2003). The principal source of information are the catalogs ARIHIP (Wielen et al., 2001) and TYCHO-2 (Høg et al., 2000), and the rich observation material (variations of latitude / Universal time) obtained during the 20th century in programs of monitoring Earth orientation. The main idea is to combine these two sources together.

The first version EOC-1 (Vondrák and Ron, 2006) was based on the combination of the observations made only in local meridian with ARIHIP, TYCHO-2, and some other catalogues. Later the observations by the method of equal altitudes (astrolabes, circumzenithals) were added, and the version EOC-2 constructed (Vondrák, 2004). This version was based on almost about 4.5 million individual observations made with 47 different instruments at 33 observatories all over the world, in the interval 1899 – 2003. The observations of latitude started in 1899, while the universal time observations were limited to period after 1956, when the International Atomic Time (TAI) became available.

The observed stars were identified in the following catalogs, from which the positions, proper motions, parallaxes and radial velocities were taken over: ARIHIP (2995 entries); TYCHO-2 (1248 entries); Hipparcos (144 entries); PPM (28 entries); local catalogs of individual observatories (3 objects). These stars formed zero-version catalog, called EOC-0, containing 4418 different objects (stars, components of double stars, photocenters).

The stars were checked for multiplicity whenever the statistically significant deviation of observed positions from catalog entry was met. In case of double stars, the displacement of the reference point (very often photocenter) was estimated and the position in EOC-0 was corrected. The individual values of deviations of measured universal time δUT, latitude $\delta\varphi$ and altitude δh from the catalog EOC-0 were then computed as the deviations from the mean value of the night, based on only astrometrically excellent stars.

To combine individual observations with catalog entry in EOC-0, the catalog is represented by three virtual observations of right ascension and declination in three epochs $t_1=t_0 - 90$y, $t_2=t_0$ and $t_3=t_0+10$y, where t_0 is the mean epoch of the catalog. Standard errors of these virtual observations, based on standard error of position and proper motion, are then calculated and used to determine their weights. They are chosen so that a linear regression through the three virtual observations yields exactly the original catalog entry, including the original standard errors. The weights of the real individual observations are all equal to 1. Linear regression through all observations (including the virtual ones) then provides the positions and proper motions of EOC-1 and EOC-2.

Because the periodic character of the residuals for certain stars was evident, another version of the catalogue, called EOC-3 was constructed later (Vondrák and Štefka, 2007), containing information on the periodicity of some of the observed objects. To this end, the same Earth orientation observations as in preparing EOC-2 were used. It was made in two independent steps:

- Improvement of positions and proper motions (identical with the procedure used for EOC-1 and EOC-2);
- Looking for periodic changes by analyzing annual averages of residuals (using spectral analysis proposed by Lomb (1976), and looking for periods in Sixth Catalog of orbits of visual binary stars (Hartkopf et al., 2006). In a positive case, the residuals were used to estimate sine/cosine terms of up to two different periods and their second-order higher harmonics, i.e., up to 16 sine/cosine terms. EOC-3 thus contains 586 objects with periodic motions.

Later some disadvantages of this catalog were discovered – the periodic terms are based on annual averages, not individual observations, which can lead to somewhat diminished amplitudes for shorter periods; and the periodic terms are derived independently of the positions and proper motions, which causes that the EOC-3 positions, calculated for the mean epoch of original catalogs (ARIHIP, TYCHO-2...) often significantly differ from the positions in these catalogs. Therefore, a new catalog EOC-4 was constructed, based on the idea that positions, proper motions and periodic terms are estimated in one-step solution, derived from combination of individual and virtual observations. First outline of this work and its main ideas were published by Vondrák and Štefka (2008).

The objects with periodic parts in EOC-3 were inspected again and some values of the periods were slightly changed. The total number of stars with periodic motions is equal to 599.

The following solutions of Earth Orientation Parameters, based on Earth Orientation Catalogs, were made:

- OA97 (Vondrák et al., 1998), OA99 (Vondrák et al., 2000), and OA00 (Ron and Vondrák, 2001) that were based on original Hipparcos Catalogue with only some of the proper motions improved;
- OA04 (Vondrák and Ron, 2005) with EOC-2;
- OA07 (Vondrák, Ron and Štefka, 2008) with EOC-3;
- OA10 (Vondrák et al., 2010) with EOC-4.

3. EOC-3 STATISTICS

The star catalog EOC-03 is available at Internet server (http://vizier.cfa.harvard.edu/viz-bin/Cat?J/A%2BA/463/783). The distribution of celestial coordinates, proper motions, parallaxes and magnitudes of the EOC-3 stars are given in Figures 1-7. The most EOC stars are distributed over the North sky, due to dominated number of observatories at the North hemisphere.

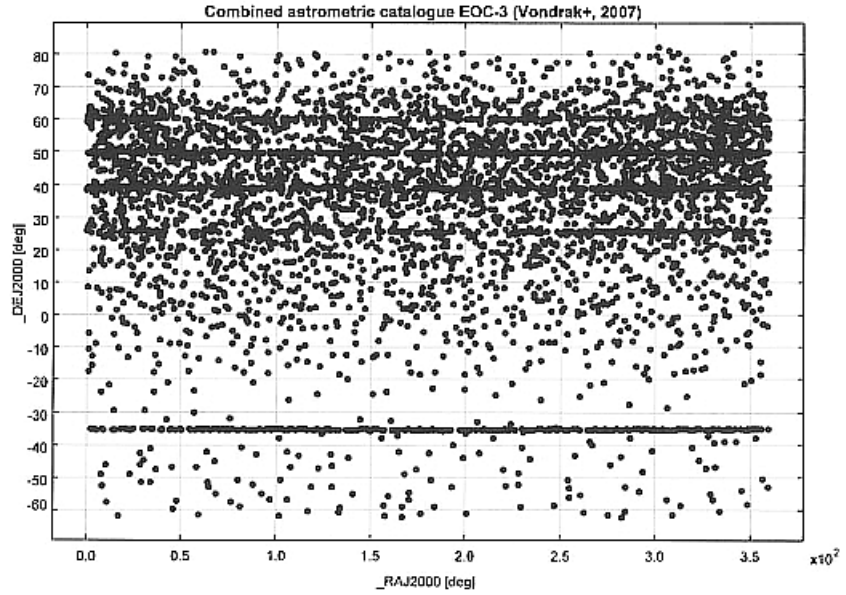

Figure 1. Celestial map of the star from the combined astrometric catalogue EOC-3.

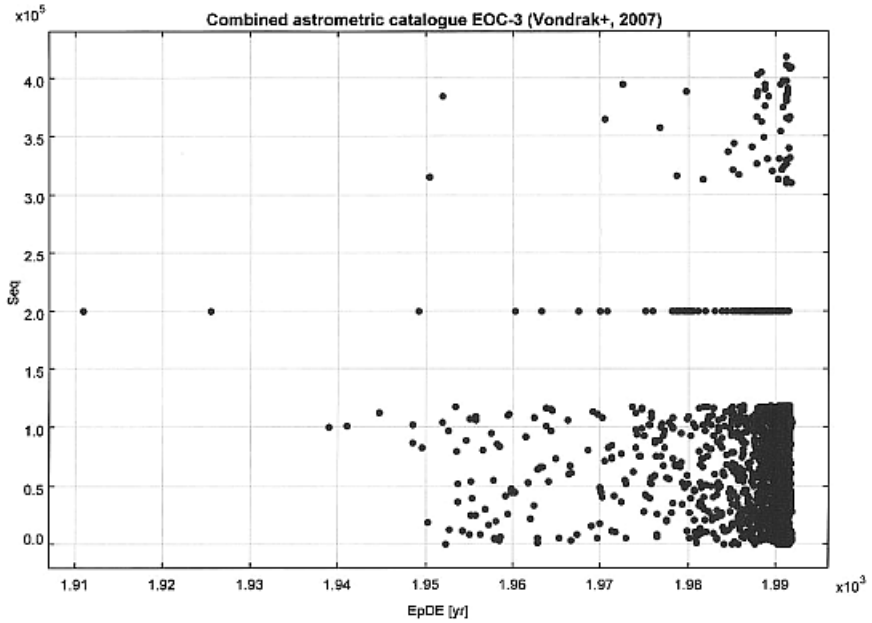

Figure 2. Epochs of the declinations of the stars from the combined astrometric catalogue EOC-3.

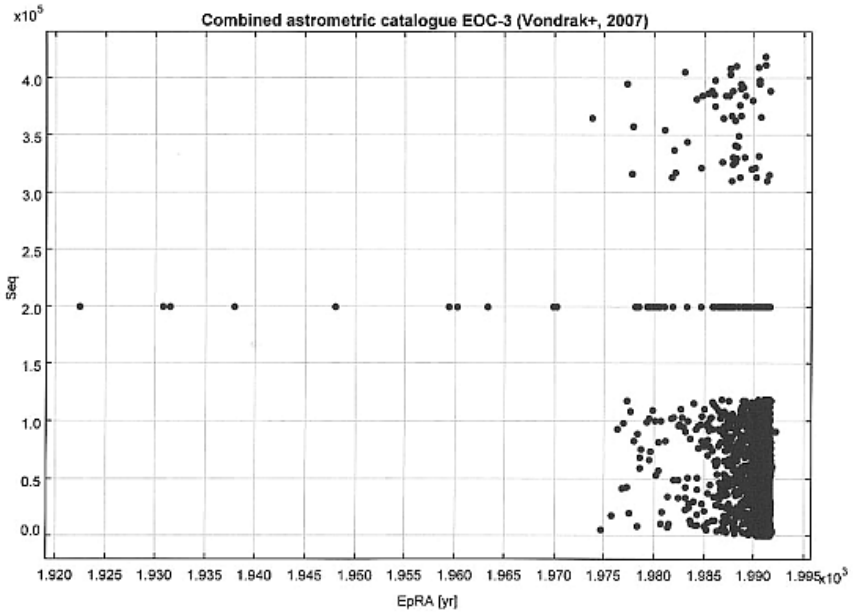

Figure 3. Epochs of the right ascensions of the stars from the combined astrometric catalogue EOC-3.

A significant part of the epochs of declinations and right ascensions of the EOC stars are before 1990. Some observational series of latitude variations cover time spans longer than 50 years and series of UT variations are shorter. These observational series are useful for proper motion improving.

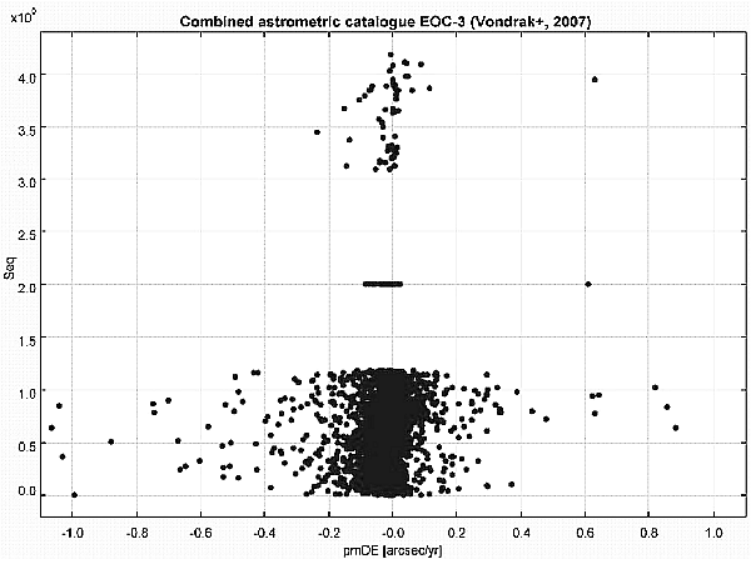

Figure 4. Proper motion in declination of the stars from the combined astrometric catalogue EOC-3.

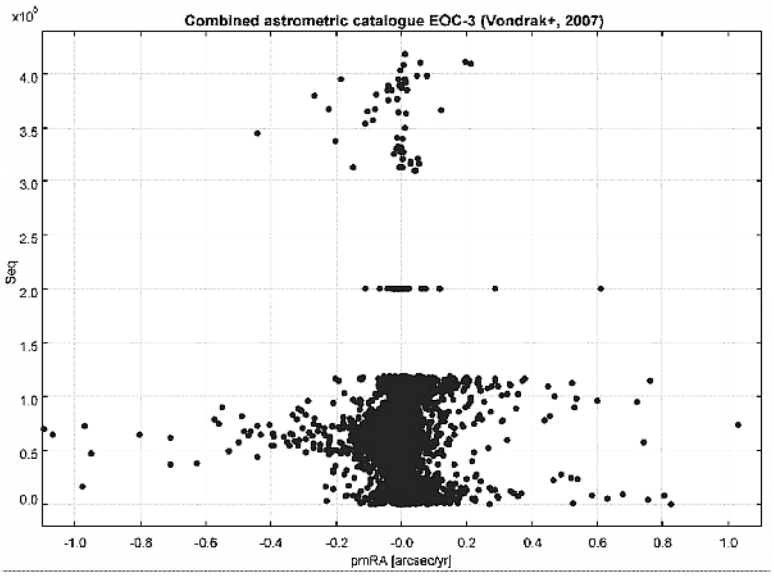

Figure 5. Proper motion in right ascension of the stars from the combined astrometric catalogue EOC-3.

A significant part of EOC stars have values of their proper motions in declination and right ascension greater than 0.1arcsec/a. These stars are with relative high absolute errors of the proper motion and they are potential candidates for proper motion improving.

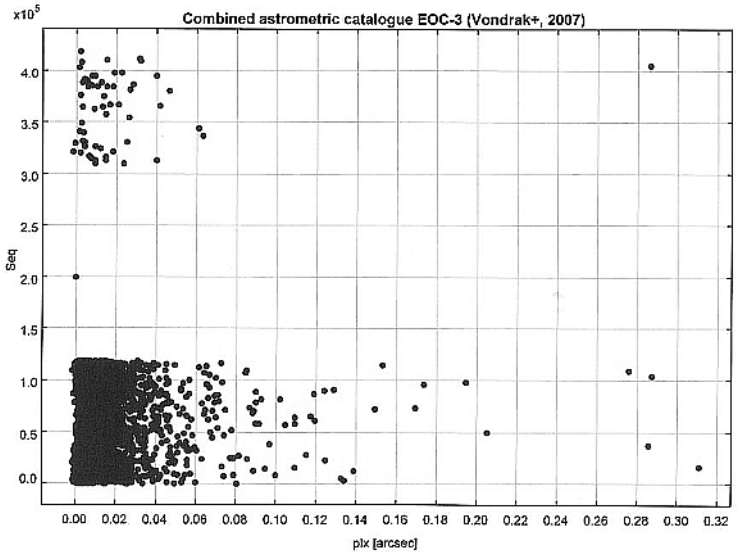

Figure 6. Distribution of the parallaxes of the stars from the combined astrometric catalogue EOC-3.

Some part of EOC stars are relatively close to the Earth as it is seen from the distribution of the parallaxes in Fig.6. These stars offer better resolution for their nonlinear motions and better possibility for successful detection of the double stars over a century observational spans. The magnitudes of the stars from the combined astrometric catalogue EOC-3 are below 12 (Fig.7). The most observed stars are with magnitude between 5 and 8 and minor part of stars is with magnitudes below 5. The bright stars cover several pixels in digitized astronomical images, which allow determining their coordinates with significant higher accuracy than the image resolution.

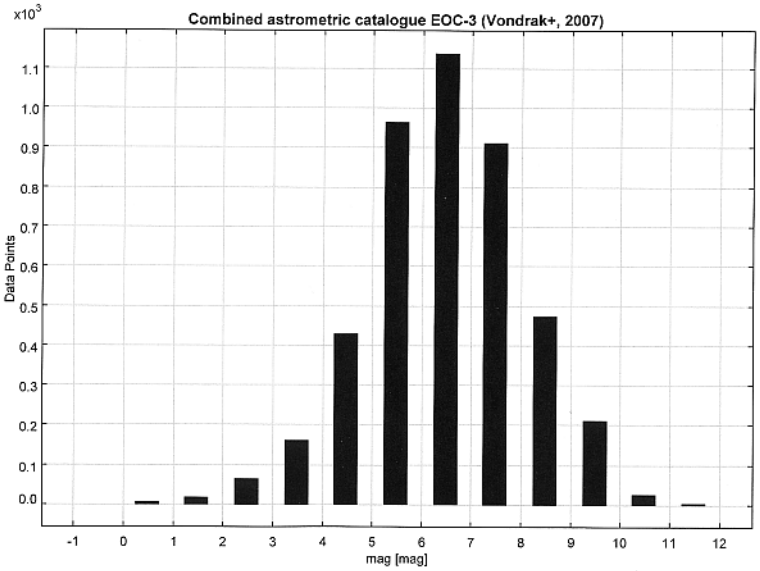

Figure 7. Distribution of the magnitudes of the stars from the combined astrometric catalogue EOC-3.

4. WIDE FIELD PLATES DATA BASE (WFPDB)

The Wide-Field Plate Data Base (WFPDB) is an information project of the Institute of Astronomy, Bulgarian Academy of Sciences, (IA) since 1991, which was initiated by a working group of the IAU and is unique of its kind on international scale (www.skyarchive.org). More than 150 000 plates from the European archives are stored and a collection of images of size of the order of 2TB is prepared. It has the potential of growth to more than 1000 TB. At present WFPDB consists of the following active interconnected parts: The Catalogue of Wide-Field Plate Archives (CWFPAs) and The Catalogue of Wide-Field Plates Indexes (CWFPIs). The CWFPAs http://www.skyarchive.org/catalogue.html is in a table format and describes the world-wide astronomical plate archives (Tsvetkova and Tsvetkov, 2006). The CWFPIs gives a complete information for the stored photographic plates (Tsvetkov at al., 2007). According to the CWFPAs,

the full number of the astronomical observations on photographic plates is estimated to ~2 200 000. It contains information about objective and informative observations that cover the longest possible period of observations in astronomy - about 130 years. According to the CWPPIs, the data for about 531 000 astronomical plates are searchable through the web-based system of WFPDB, http://www.skyarchive.org/search.html. The WFPDB is unique with its internationally accepted standard for description of astronomical photographic observations into various archives. The enlarged regularly updated and developed version can be found since 2001 at Sofia Sky Archive Data Center giving information about 119 distributed plate archives and on-line access to their prepared computer-readable catalogues with about 531 000 plates. We may expect a wide use of digitized astronomical plates in star catalogs improving when the most of the existing plates will be digitized and free and fast access to them will be available.

4.1. Telescopes and digitized plates in WFPDB

A lot of different instruments had been used in the last century to create the astronomical plates. The used telescope have individual field of view, aperture and focal length. The WFPDB telescopes have the following fields of view and aperture:

- Field of view [degree]
- **1, 3, 5, 7**, *20, ...;*
- Aperture [cm]
- *10, 12, 14, 16, 34,* **40, 60, 67**, …

The telescopes with the field of view of 20 and more degrees have poor angular resolution and their astronomical plates are not compatible with the accuracy of the modern star catalogs. The same situation is with the small telescopes whose aperture less than 40cm. Thus, it is possible to filtrate the astronomical plates for star catalogs improving by choosing images from instruments with field of view 1-7degrees and aperture greater than 40cm. The WFPDB contain information about images with various plate scales – from 13arcsec/mm to 860arcsec/mm. The useful plate scales are below 115arcsec/mm, which allow astrometrical determination with sufficient accuracy. The most often used resolution for image scanning is 2400dpi, small number of plates is scanned with a higher resolution, but image preview is available with resolution 300 – 600dpi. The resolution 2400dpi is rather enough for astrometrical purposes.

- Plate scale ["/mm]
- - *860, 830, 295, 258, 300,* **115, 102, 96**, …
- Scan resolution [dpi]
- - 300, 600, 1200, **2400, 4800,** …

4.2. WFPDB's star position accuracy

The star position in the frame of the digitized astronomical plates should be determined with high enough accuracy in order to use the images for star catalog improvement. The maximum accuracy of a given star image is the angular size of a single pixel. It depends on the mean size of the silver grains from the plate emulsion, too. If we assume the mean silver grain size of about 10μm, then the expected accuracy will be as follow:

- According plate scale (emulsion grain 10μm)
  - 100"/mm - ±0.5"
  - 60"/mm - ±0.3"
  - 13"/mm - ±0.06" (Observatory Rozhen)

The realistic maximum accuracy of a single star position determination is between 0.3arcsec and 0.5arcsec, but it depends on scan resolution, too:

- According scan resolution
  - 300dpi=12d/mm+scale 13"/mm - ±0.5"
  - 600dpi=24d/mm+scale 13"/mm - ±0.3"
  - 1200dpi=47d/mm+scale 60"/mm - ±0.6"
  - 2400dpi=94d/mm+scale 100"/mm - ±0.5"
  - 4800dpi=189d/mm+scale 100"/mm – (±0.3")
  - 9600dpi=378d/mm+scale 100"/mm – (±0.1")

It is possible to achieve the maximal accuracy by means of different scan resolution, even from preview images with 300dpi, in the case of combination with proper plate scales.

5. CONCLUSIONS

The optical astrometry data consist of more than 4 million observations of more than 4000 stars or star pairs, collected from 33 observatories since 1899. These observations are the only centenary series, used for determination of the variations of the local plumb-lines and Earth rotation and give us unique possibility of searching causality between these variations and global changes of the environment, climate, solar activity, ice melting and post-glacial rebound, mean sea level arising, earthquakes etc. Necessary precondition of successful utilization of the astrometrical observations in the field of modern scientific investigations is the improvement of the accuracy of star catalogues, where the proper motion of the stars (or their annual velocity on the celestial sphere) is a critical parameter. The Earth Orientation Catalogs (EOC) are primarily meant to provide stable celestial reference frame in optical wavelength for deriving Earth Orientation Parameters (EOP) from astrometric observations.

Some observational series of latitude variations cover time spans longer than 50 years. These observational series are useful for proper motion improving. A significant part of EOC stars have values of their proper motions in declination and right ascension greater than 0.1arcsec/a. These stars are with relative high

absolute errors of the proper motion and they are potential candidates for proper motion improving. The most observed stars are with magnitude between 5 and 8 and minor part of stars is with magnitudes below 5. The bright stars cover several pixels in digitized astronomical images, which allow determining their coordinates with significantly higher accuracy than the image resolution.

The WFPDB provide significant number of plates, containing a given star. The observation epochs cover century time span, which is useful to improve star catalogs. It is necessary to improve the free access to the digitized plates and to add some new options in the search engine and tools:

- compressed images with resolution 2400dpi or more
- search for plates with scale <100arcsec/mm
- online tool for identification of a group of stars from a given plate sequence
- accurate determination of the plate centers and their orientation by 7-parameter transformation.

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