Old photographic plates in the Gaia era: archive plates of Pulkovo observatory, its digitization, results of astrometric reduction, error analysis

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Introduction

At present, the "glass archive" of Pulkovo Observatory contains 52800 photographic plates with images of various celestial objects (stars, natural satellites of planets, the selected asteroids, visual-double stars, globular and open star cluster and etc.). Metadata of all plates has been collected in the database for each telescope. FITS-format is used for archiving the metadata. As of today the information about plates of Normal astrograph and 26-inch refractor is available via the Pulkovo Photographic Plates Database (www.puldb.ru/db/plates).

Automatic digitization of the pulkovo plates has been begun on the flatbed scanners. The UMAX Power Look II scanner was used at work in the small fields (with a radius < 20' from the optical center of the plate) and the Microtek ScanMaker i900 scanner was used at work in large fields (2^ox2^o). The part of the plates was digitized using the Damian digitizer in ROB. In 2012 in the Laboratory Astrometry and Stellar Astronomy the Mobile Digitizing Device was mounted for mass digitization of photographic plates. Errors that accompany the process of digitizing of the photographic plates, of measuring of images and of astrometric reduction are analyzed for different types of digitizing devices.

1. Tasks of modern astronomy for solution which data of photographic observations may be useful

1.1. *The study of the dynamics of planetary satellites and asteroids, construction of dynamical models for these objects.*

Solution of these tasks requires of high accuracy of the observational data and of long the periods of observations. The new reduction of the digitized photographic plates would enable to get series of observations lasting for 50-100 years. This will be a significant contribution in solving of this problem.

The accurate theories of motion of planetary satellites and asteroids are needed to the ephemeris support of ongoing and future space missions to these objects. The study of dynamics of planetary satellites and asteroids will make it possible to understand the mechanism of formation and evolution of the Solar system.

1.2. *More precise determination of proper motions faint stars.*

New reduction of the digitized plates enables to get additional data for early epochs of such stars to determine their proper motions with high level accuracy. It is particularly important for stars with magnitude large than 13.5. The lack of high accuracy of proper motions of faint stars is a problem of all modern catalogues.

Accurate proper motions of stars are the key material for studying the kinematics and structure of various Galactic subsystems, its analysis allows to understand the mechanisms of star formation in the various subsystems of the Galaxy, to clarify the dependence of the «mass-luminosity relation» and etc. A high level of accuracy of obtained long-term averaged proper motions of faint stars may be useful in analyzing the proper motions of the GAIA catalog, to identify the binary and multiple systems among the faint stars.

1.3. *Different researches of separate objects of scientific interest.* Such objects can be:

- Visual-double stars
- Stars with invisible companions
- Stars with large proper motions (special interest is caused by white, red and brown dwarfs in the solar neighborhood) and etc.

The old plates are the additional material for such researches. For an example, we were needed accurate proper motions of the low luminosity stars when searching for candidates in astrometric binary among dwarfs. New proper motions of 1500 stars in the zone of declination $+70^{o}$- $+40^{o}$ were obtained from a combination of CCD-observations by Pulkovo normal astrograph and of data catalogs and digital sky surveys (2MASS, SDSS DR8, CMC14, and M2000). The average accuracy of new proper motions was 4 mas / year.

Additionally, for 832 stars (14-16 mag) the new proper motions were obtained from combination of the Pulkovo CCD-observations with the observations of these stars, which were found on the 1800 digitized photographic plates (observations made in 50-ies). It was an experiment on the use of the old plates. The accuracy of the proper motions of 832 stars was within 2 - 8 mas / year. It's not a bad accuracy for proper motions of faint stars.

139 candidates in the astrometric binary were found among the 2332 low luminosity stars.

2. Basic sources of errors when digitization, measurement and reduction of photographic plates

There are three main sources of errors:

- Errors of digitizing device
- Errors of astrometrical reduction
- Errors, which depend on the quality images on the photographic plate.

This is enough conventional division, as in the process of measuring and reducing, errors of different types of transformed, into each other and sometimes cancel out. In particular, the errors of third type, conditioned by errors of lens telescope, atmospheric conditions during the observation, state of emulsion of photographic plates, can significantly affect the errors first and second types.

3. Errors of digitizing devices

Basic types of flatbed scanners systematic errors

- variation of pixel width in different parts of the CCD sensor (results in $\Delta x(x)$ error).
- curvature of the CCD sensor (results in $\Delta y(x)$ error).
- curvature of the guide, along which the CCD sensor is moved (results in $\Delta x(y)$ error).
- variation of the speed of CCD sensor movement along the guide (results in $\Delta y(y)$ error).
- non-orthogonality of scanner's axes.

All these errors have associated with the technology of production of inexpensive flatbed scanners.

Errors DAMIAN digitizer

- lens distortion
- non-orthogonality of X and Y axes (approx. 10 arcsec).
- tilt of the optical axis of the objective
- digitization noise (quantization noise) of the CCD sensor (result in inaccuracy of fitting of the profile)

The most significant error is the lens distortion. The remaining errors are small.

Errors Mobile Digitizing Device (MDD)

- various aberrations of the lens
- digitization noise (quantization noise) of the CCD sensor

The most significant errors are various aberrations of the lens but they are stable enough.

4. Calibration of Digitizing Devices

The systematic errors of different the digitizing devices require calibration of these devices before the measurement of photographic plates. We did not have any problems with the measurements of objects using UMAX flatbed scanner in the small fields near the optical center of the plate. Serious problems began with measuring over a wide field (2^ox2^o). All errors of the flatbed scanners have revealed itself to a full extent. To determine these errors, their correction and determination of the measured coordinates of stars software package SCANSOFT has been created. For calibration the Microtek flatbed scanner and the Damian digitizer we used photographic plates with a large density of stars (Pleiades).

The systematic errors of the flatbed scanner were presented as the sum of two independent components: a constant part and variable. To determine the constant part of the systematic error, the plate for the calibration was digitized in 4 positions with the rotation by 90 degrees and in each of these positions again 5 times with a shift to the right and with the turn to any angle. Thus, to determine the required corrections 20 scans of the plate were obtained. Constant part of systematic error was determined once in 10 months. Variable part was determined individually for every measured plate (Khrutskaya et al. 2012).

For calibrate the Damian digitizer our method of calibration was slightly modified. The plate for calibration was digitized at the four positions with the rotation by 90 degrees. It was been assumed that values of systematic errors and them the structure are identical in all sub-images of size 704x704 px. The everyone sub-images (704x704 px) of overall mosaic image were divided into 8 parts in X and Y directions. The size of such small fields is 88x88px.

The aim of the calibration – the determination of systematic errors of the DAMIAN digitizer for each small field of size 88x88 px.

The residual errors of constant part of systematic component for the Microtek flatbed scanner have not exceeded of the 2 micron. For the Damian digitizer, the residual systematic error have not exceeded of the 0.3 micron.

5. Digitization of photographic plates. Determination of the measured coordinates (X, Y) of objects.

With digitization of plates using the flatbed scanner, each plate was digitized in four positions with rotation by 90 degree (to reduce random errors and exclusion the variable part of systematic error). With digitization of plates using the DAMIAN digitizer all plates were digitized in one position.

Further work has included:

- exclusion of non-stellar objects
- separation of exposures relevant to each object, the averaging coordinates for these exposures
- exclusion of objects which were measured with low precision (only for flatbed scanner)
- introduction of systematic corrections in the measured coordinates (X, Y).

Lorentz profile was used to fitting of digitized images. The average error of the measured coordinates (X, Y) on one plate was 0.9-1 microns for the flatbed scanner and 0.2-0.3 microns for the Damian.

6. Astrometric reduction

For the astrometric reduction, the six-constant method has been used. UCAC3 was used as a reference catalog. The residual systematic errors (coma, distortion, and the magnitude and color equations) were taken into account. Given the problems with accuracy the proper motions of stars in the catalog UCAC3 in the northern hemisphere (Roeser et al., 2010), for the reduction we did not use the stars, if they answered the following conditions:

- the number of catalogues for the determination of their proper motions was less than 3
- total proper motion was larger than 150 mas / year
- magnitude was larger than 14.5

In most case exclusion of reference stars was made on account of the first condition. Stars which were left for the reduction had more accurate proper motions. The system of these proper motions more corresponded with the idea of how the proper motions of stars must change with their positions on the celestial sphere based on the models of solar motion relative to the centroid of the considered stars, galactic rotation, and local deformation of the velocity field in the Oort solar neighborhoods (Khrutskaya et.al, 2011).

The residual differences of the form (O-C) of reference stars were analyzed in order to identify the systematic errors. We had 460,000 such differences for 1800 plates, which was digitized by a flatbed scanner.

The differences (O-C) include various errors:

- Residual errors of the digitizing device
- Systematic and random errors of the reference catalog,
- Errors associated with a telescope and conditions of observations.

The dependence of values (O-C) from magnitude showed the presence of significant magnitude equation. Vector fields of the residual differences (O-C) showed that the systematic effects are differ in value and structure in the different intervals of magnitudes. Vector fields were used to determine the systematic corrections to the coordinates of the stars.

7. The quality of the photographic plate

Various factors affect the quality of images of objects on a photographic plate:

- State of the emulsion, grain size of the emulsion
- Errors of a telescope objective
- Atmospheric conditions during the observation period.

It should be noted that the state of photographic emulsion varies with time. We did not make of own researches of influence of the distortion in emulsion on the digitized image. However, by available researches (J.F. Lee, W. van Altena, 1983; N.C.Hambly et al., 1998) the accuracy of the digitized images can not be better 0.1 - 0.4 micron due to the quality of the emulsion and the grain size of emulsion.

When measuring the Pulkovo plates, it was observed that the accuracy of determination of PSF parameters on the plates of good quality and on the plates with a fog is not much different, if Damian digitizer had used for digitizing (average accuracy about 0.01 px). For the flatbed scanner, accuracy gets noticeably worse (to 0.05 px) for plates with a fog.

8. The results of new reduction of Pulkovo photographic plates with selected asteroids and Pluto using the Damian digitizer

Now the new reduction is completed for all the digitized plates, among these - 167 plates with selected asteroids and 62 plates with Pluto.

Mean precision of astrometric reduction (error unit of weight) is 85-105 mas for RA and DECL (fig.1).

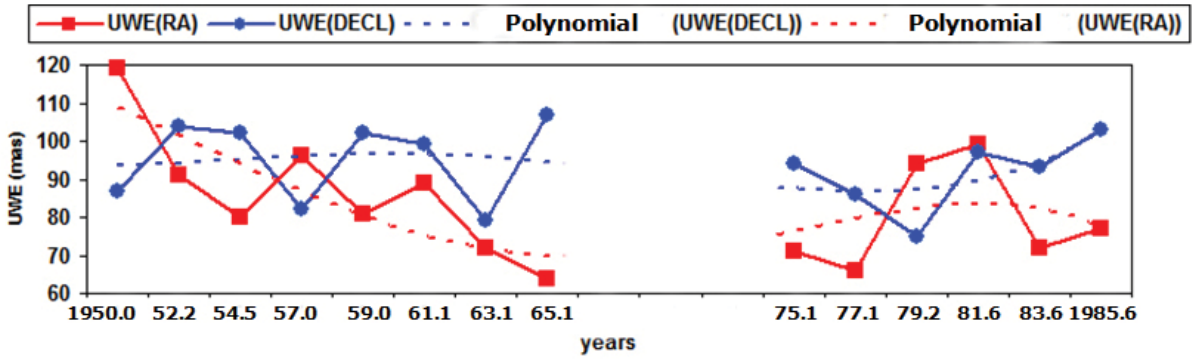

Fig.1. The average errors of astrometric reduction (UWE) for the observation period from 1949 to 1987 in RA and DECL. Unit: mas

The accuracy of a single asteroid observations lies within 60-150 mas for both coordinates (average accuracy - 130 mas)

To comparing, the accuracy of a single observation of same asteroids was 180-200 mas, if PPM as reference catalog and ASCOREKORD device for measuring were used

More high accuracy of one observation when new reduction, is cumulative effect from using more accurate measuring device, of a modern high-precision reference catalog and more thorough accounting of residual systematic errors.

The Pluto was observed at Pulkovo from 1930 to 1994. 272 photographic plates were obtained during this period. 62 plates with Pluto (observation period 1930-1960) were digitized using the Damian digitizer

Average precision of a single Pluto observation is: $\varepsilon RA\cos\delta$=153 mas; εDECL= 107 mas.

To comparing, the accuracy of a single observation of Pluto was $\varepsilon RA\cos\delta$ = 260 mas, εDECL = 200 mas, when REPSOLD meter was used for measurement of plates and Yale catalog, translated into FK3 system, as reference catalog was used (Lavdovsky. 1968, period of observations 1930-1965).

Comparison of the Pluto observations with DE405 ephemeris was made apart for the two periods (tab.1). Can see that agreement of the observations with ephemeris is better in the second period. Service of IMCCE was used to calculate the ephemeris (http://www.imcce.fr/fr/ephemerides/generateur/.htm).

Table 1. Comparison of the Pluto observations with DE405 ephemeris

	Obs. 1932-1941 (25 plates)				Obs. 1949-1960 (37 plates)			
Eph	(O-C)$\alpha\cos\delta$	σ(O-C)α	(O-C)δ	σ(O-C)δ	(O-C)$\alpha\cos\delta$	σ(O-C)α	(O-C)δ	σ(O-C)δ
DE405	-0".475	0".073	-0".099	0".037	-0".230	0".037	-0".132	0".025

Since nowadays there is no reliable theory of Pluto's motion, it is extremely desirable to make digitization and new reduction of the plates with Pluto using all available observations worldwide, especially during the 1930-1940.

Conclusion

1. Digitization of the pulkovo plates, their measurements and new reduction have shown that the DAMIAN digitizer can be used for high-precision astrometric measurements.
2. In the near future it is extremely desirable to make digitizing and new reduction of the plates with Pluto using available observations worldwide, especially during the 1930-1940.
3. The plates which were obtained with only one exposure should be digitized twice with rotation of the plate by 180 degrees. It will increase the accuracy of the measurement coordinates (X,Y) and will enable to exclude non-stellar objects more reliably.
4. More high accuracy of single observation in time of new reduction is due cumulative effect from using more accurate measuring device, of a modern high-precision reference catalog, and more thorough accounting of residual systematic errors.
5. Various systematic errors and their changes must be determined from the analysis of the entire set of observations of the object by concrete telescope. Only in this case can minimize the impact of local errors and to get a homogeneous material. The latter is very important to clarify the parameters of dynamic models of planetary satellites and asteroids.
6. From experience of the digitization of the pulkovo plates can said that about from 10 to 15% of the plates no point digitize because of poor quality, else from 5 to 10% get into defective after reductions for different reasons:
    - large errors of measurement,
    - errors in the metadata,
    - loss of the object (erroneous rejection of a real object in the time of exclusion of non- stellar objects) and etc.
7. In future, under the using of GAIA catalog for re-reduction digitized photographic plates can be expected to improve the accuracy of the results. Two factors will contribute to this: the high astrometric accuracy of the data in GAIA catalog and a large density of stars. However, it should be borne in mind that the large density of stars in Gaia catalog will be achieved by adding to the catalog of a significant quantity of faint stars (mag> 13), so the most noticeable increase in accuracy can to wait for the objects fainter than 13-14 magnitudes (faint planetary satellites, faint asteroids and objects of such as Pluto).

For the brightest planetary satellites (5-8 mag) increase in accuracy can occur only due to the higher precision of the bright stars in GAIA catalogue and it will be less significant. The attraction of faint reference stars for the reduction of the brightest objects is not the best variant of the astrometric reduction, because this will lead to systematic errors associated with magnitude equation, which will be need to exclude.

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