International Workshop
A new reduction of old observations in the Gaia era
Paris Observatory, June 20-22, 2012

Central Astronomical Observatory of RAS at Pulkovo.

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

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As of today 52800 photographic plates are stored in the Archive of the Pulkovo observatory

Temperature: +19ºC - 22ºC
Relative humidity: 55-60 %

*an archive of photographic plates of Pulkovo observatory*

*a room for work with photographic plates.*

## Instruments which were used for photographical observations (all sizes are given in millimeters)

- PNA normal astrograph at Pulkovo (D=300, F=3400)
- P26 26-inch refractor at Pulkovo (D=650, F=10413)
- AKD short-focus double astrograph at Pulkovo (D=100, F=700)
- LPT lunar-planetary telescope In Ordubad expedition (D=700, F=10000)
- FAS FAS-3A camera in Ordubad expedition (D=250,F=480)
- PT Polar tube at Pulkovo (D=200, F=6000)

- BSch Schmidt telescope at Baldone (Latvia) (D=1200, F=2400)
- ZDA Zeiss double astrograph in Abastumani (Georgia) (D=400, F=3000)
- EA expeditional astrograph in Bolivia (D=200, F=2260)
- Z160 Zeiss camera in Cuba (D=160, F=700)
- Z400 Zeiss telescope at Zelenchuk (D=400, F=2000)

## Objects on the photographic plates

- Major planets and their natural satellites
- Selected minor planets (asteroids)
- Comets
- Moon
- Double and multiple stars, and stars with invisible companions
- Globular and open star clusters
- Pleiades
- Fields with extragalactic nebulae (according to A.N.Deich's plan)
- Kapteyn selected areas
- Fields with galactic and extragalactic radio sources
- Stars of FKSZ (program of faint stars of northern sky)
- Geodesic stars
- Reference stars of southern sky (FOKAT program)
- Near-pole stars
- Supernovae

etc

## The number of photographic plates with images of the Solar system bodies and observation periods.

- Saturn and its satellites – 800 plates (1972 - 2007).
- Jupiter and Galilean satellites – 500 plates (1976 – 2005).
- Mars – 763 plates (1960 - 1988).
- Uranus and its satellites – 250 plates (1910-2004).
- Neptune – 237 plates (1899 - 1955).
- Pluto – 272 plates (1930 – 1994)
- 18 selected asteroids – 2655 plates (1949-2004)

# Pulkovo Photographic Plate Database

To find a certain plate, type its number, choose instrument and click button FIND

Instrument: Normal Astrograph | Plate number: [ ] | FIND

← a choice of the separate plate

To find plates with a certain sky area: choose instrument, type coordinates (R.A. and Dec.) of the center of this area, type radius of this area, type (optionally) names of required objects, and click button FIND

← a choice of all plates in a certain area of the celestial sphere

Instrument: Normal Astrograph
R.A.: [ ] (h m s), Dec.: [ ] (d m s)
Search radius: [ ] (d m s)
Object: [ ] or [ ] or [ ]
Maximum number of lines to show: 100
FIND | Reset form

To find plates with a certain object, fill one or more of fields below, choose instrument and click button FIND

← a choice of plates with a specific object, using it name or number

Instrument: Normal Astrograph
Plate numbers between [ ] and [ ]
Year between [ ] and [ ]
Object: [ ] and [ ] and [ ]
Object: [ ] or [ ] or [ ]
Plates with minor planet number [ ]
Maximum number of lines to show: 100
FIND | Reset form

Description | Main Page

VIEW DATA: Record number 4250

FITS TEXT CLOSE THIS WINDOWS

Instrument: NAP
Plate number: 06658
Object: minor planet PARTHENOPE [МП11]
Date: 1960 01 28

RA: 5 12 42.00
RA (J2000): 5 15 03.48
DEC: 19 41 00.0
DEC (J2000): 19 43 40.0

Time: 05 57 00.00
06 01 00.00
06 03 00.00
06 07 00.00
06 09 00.00
06 13 00.00
u: 36.80
Number of exp.: 3
Exp.: 3 exp x 4 min.

Size: 160*160
Emulsion: KODAK OaO
Filter: -;-
Phot.system: B

T: -15.0
B: 757.2
Focus: 28.1

Comment:
Observer: Bronnikova
Condition: well
Location: 1.2
Measured: DAMIAN
Last edited: nn 17-07-2009 13:15:31

**www.puldb.ru / db / plates**

## *The tasks in modern astronomy for solution which a material of photographic observations may be useful.*

- **The study of the dynamics of planetary satellites and asteroids, the construction of dynamical models for these objects**. To solve this problem requires a high accuracy of the observational data and the long series of observations. The new reduction of the digitized photographic plates would enable get a series of observations lasting 50-70 years. This is a significant contribution to solving this problem.

Exact theories of motion of planetary satellites and asteroids are necessary for ongoing and future space missions to these objects, to study the structure and evolution of the Solar system.

- **Obtaining of equatorial coordinates of stars in the early epochs for determination their a proper motions.** It is particularly important for stars with magnitude more 13.5. The lack of a quite level accuracy of the proper motions of faint stars is a problem of all modern catalogs.

The precise proper motions of stars are the material for studying the kinematical and physical subsystems of the Galaxy, the ability to understand the mechanisms of star formation in the various subsystems of the Galaxy, to clarify the dependence of the "mass-luminosity relation," etc.

**The observational data obtained in early eras may be useful in analyzing the proper motions of the GAIA catalog to identify the binary and multiple systems among the faint stars.**

•**Obtaining of additional material of observations to study of selected objects of scientific interest.**

Such objects may be:

- Visual-double stars
- Stars with invisible companions
- Stars with large proper motions (of special interest are white, red and brown dwarfs in the Solar neighborhood).

etc.

**For an example,** we were needed the accurate proper motions of the low-luminosity stars when searching for candidates in astrometric binary among dwarfs.

For the majority of the Pulkovo program stars new proper motions were obtained from a combination of CCD-observations by Pulkovo Normal astrograph and of data catalogs and digital sky surveys (2MASS, SDSS DR8, CMC14, M2000). **The average accuracy of the new proper motions is 4 mas/year.**

**Additionally, for 832 stars (14-16 mag) the new proper motions were derived from combination the Pulkovo CCD-observations with the observations of these stars, which were found on 1800 digitized photographic plates (observation 50-ies).** It was an experiment on the use of old plates. **The accuracy of the proper motions of 832 stars was in the within 2 - 6 mas/year. It's a quite acceptable accuracy**

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

# The history of digitizing of the Pulkovo photographic plates in the Laboratory of Astrometry and Stellar Astronomy

## UMAX PowerLook II

- model: UMAX PowerLook II
- optical resolution: 600 ppi
- number of bits per pixel (grayscale mode): 8
- maximum size of scanned plates: 200x250 mm
- time needed to scan a 160x160 mm plate: ~ 5 min
- sensor: one-dimensional CCD

We planned to use UMAX scanner for digitizing small fields with binary stars. Mass digitization of these plates began in 2009 and continues to this day. The results will be presented in a separate report.

## Microtek ScanMaker i900

- model: UMAX PowerLook II
- optical resolution: 3200 ppi
- number of bits per pixel (grayscale mode): 16
- maximum size of scanned plates: 200x250 mm
- time needed to scan a 160x160 mm plate: ~ 5 min
- sensor: one-dimensional CCD

Mikrotek flatbed scanner was purchased to digitize in wide fields (2x2 degrees or more). Mass digitization of plates with selected asteroids was started in late 2010. 2000 plates were digitized for the 6 months.

## DAMIAN digitizer at ROB

*•Manufacturer: AEROTECH (USA)*
*•Positioning system: AEROTECH ABL3600 on the granit plate 1.5m x 1.2m x 0.2m*
*Schneider Xenoplan telecentric objecrive 1:1*
*12 bit CMOS camera (BCi4), field 1280x1024 px*
*Size of pixel: 7 x 7 micron.*

In 2008-2010 was digitized 167 plates with the selected asteroids, 62 plates with Pluto, 6 plates with the satellites of Jupiter and 15 plates with the Pleiades and with the extragalactic nebulae (for calibration).

## Mobile Digitizing Device (MDD)

*Canon EOS 5D Mark II: 21.1 – megapixel full-frame CMOS digital single-lens reflex camera*
*Objective: Jupiter 21 M, long- focus of four-lens anastigmat (F=200 mm, relative aperture of 1.40 to 1.22, angle of field view 12º, resolution (center/edge) 40/30 line/mm)*

During May 2012 were digitized:
40 plates with parallax stars, 24 plates with the satellites of Saturn, 64 plates with Pluto and 450 plates with double stars.

***Basic sources of errors in the measurement and reduction of photographic plates can be divided into three categories.***

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

# *Errors of digitizing device.*

## *Basic types of flatbed scanner 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.

## *Errors of DAMIAN digitizer*

- distortion of the objective
- 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

## *Errors of Mobile Digitizing Device (MDD)*

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

# CALIBRATION

## *Flatbed scanners.*

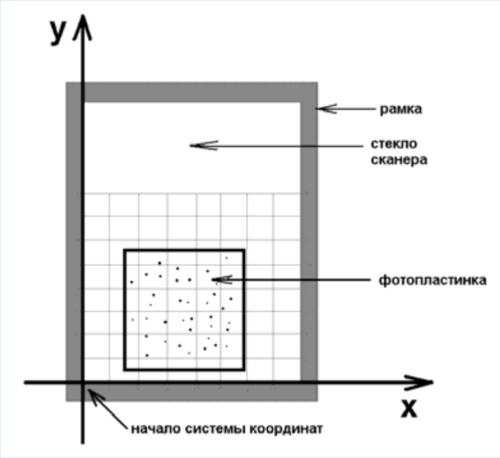



**Fig.1 Partition of the scan area into squares.**

### Constant part of systematic error (software SCANSOFT)

We divide the scan area (i.e. scanner's glass) on an imaginary grid containing M rows and M columns (fig.1).
**The gist of the calibration method - determination of systematic errors of the scanner for each square of an imaginary grid.**

Let $(\xi, \eta)$ - true coordinates of some star, and (x, y) - measured coordinates $\varepsilon x(x,y)$ and $\varepsilon y(x,y)$ - unknown corrections which represent systematic errors in different squares of that imaginary grid.

$$\xi = x + \mathbf{FW}(m)$$
$$\eta = y + \mathbf{GW}(m) \quad (1)$$

**F** is the vector of $\varepsilon x(x,y)$ corrections, **G** is the vector of $\varepsilon y(x,y)$ corrections, m is the number of the square which contains that star: $m = [x/w] + [y/w]*M + 1$ (2)
**W** is the vector representing position of that star in the imaginary grid, components of vector **W** are: W(i) = 1, if i=m, W(i) = 0, if $i \neq m$.
**Vectors F and G are common for all stars and all plates. Their components are calculated during calibration and are invariable till the next calibration.**

For each pair of scans (A, B) were constituted the conditional equation of the form (2).

$$\mathbf{FW}(m_A)\cos\alpha + \mathbf{GW}(m_A)\sin\alpha - \mathbf{FW}(m_B) = x_B - x_A\cos\alpha - y_A\sin\alpha - S_x$$
$$\mathbf{GW}(m_A)\cos\alpha - \mathbf{FW}(m_A)\sin\alpha - \mathbf{GW}(m_B) = y_B - y_A\cos\alpha + x_A\sin\alpha - S_y \qquad \textbf{(2)}$$

Systematic corrections (components of F, G) were determined using the parameters of connection between pairs of scans from the common system of conditional equations of form (2) which formed for all the stars of all pairs of scans by the method of least squares. The variable part is determined for the each plate.

**Plates with the large number of stars (Pleiades) were used for calibration.**

# An estimate of the residual systematic error of flatbad scanner.

## *Before calibration*

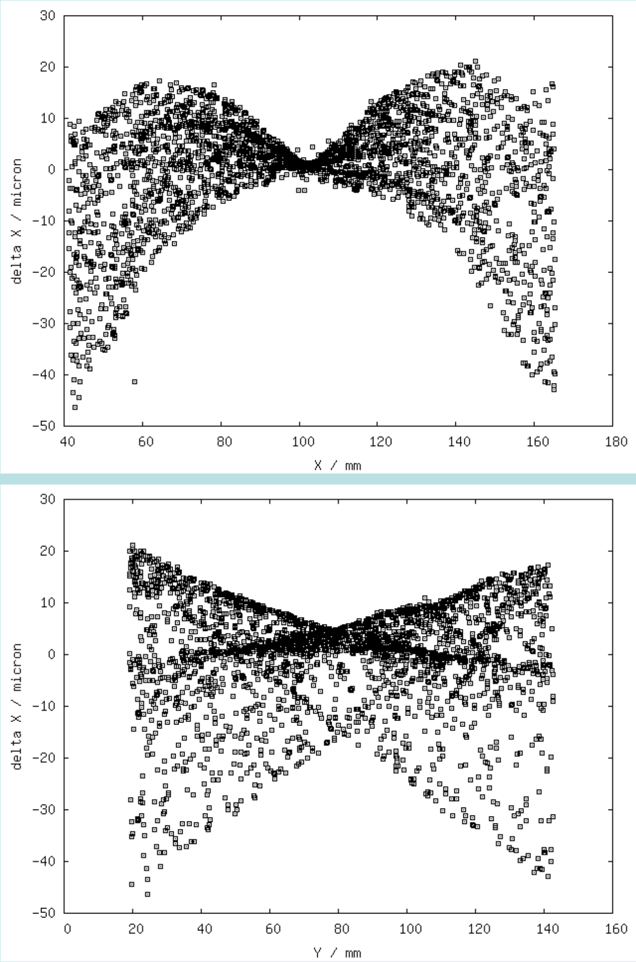



**Fig.2 Star shifts along X and Y axes *before* systematic error correction. Comparison of two scans of plate D469, 1820 stars, plate rotated by 180º.**

## *After calibration*

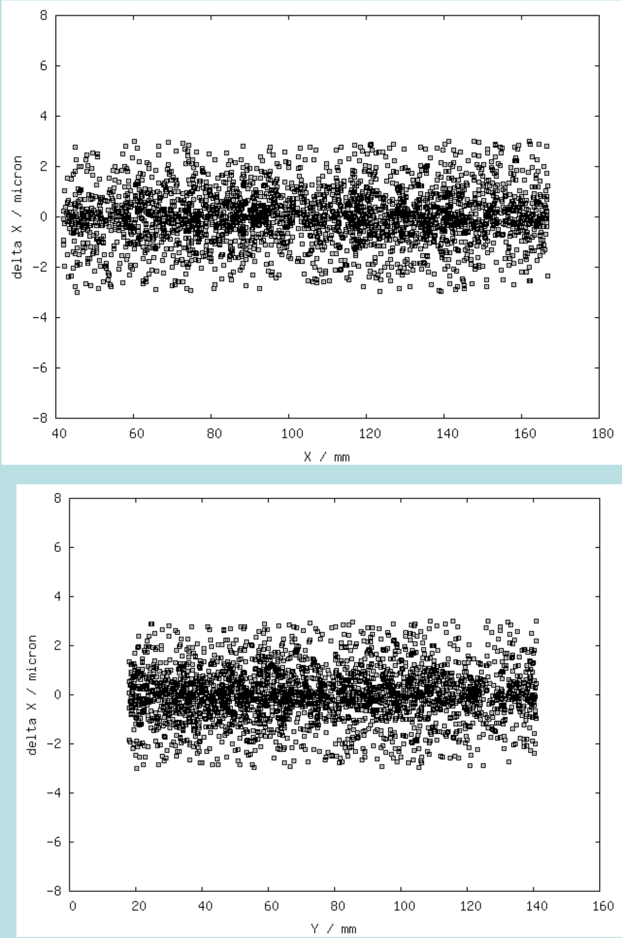
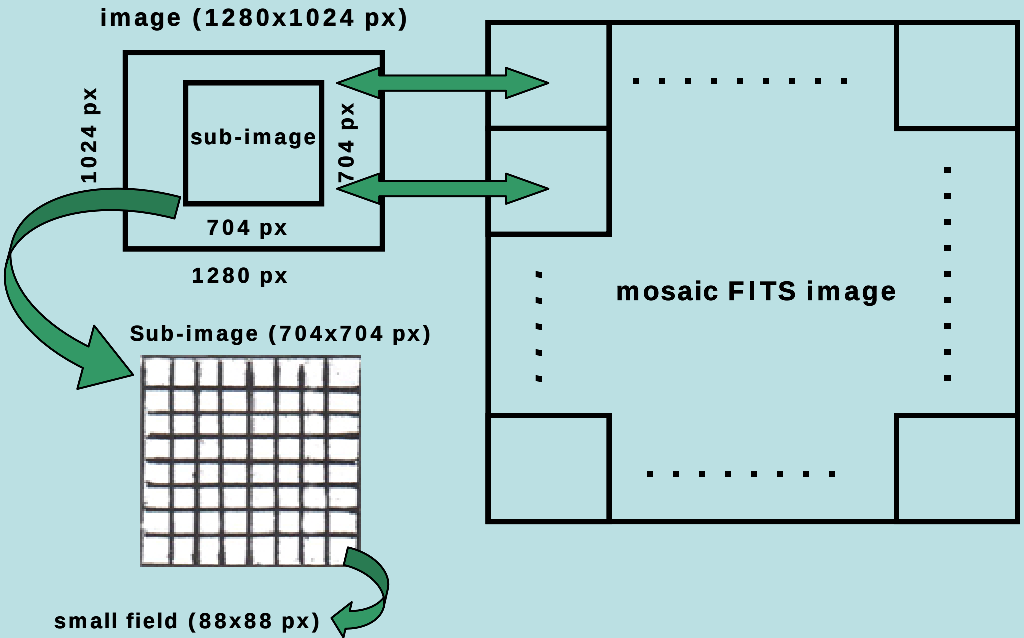



**Fig.3 Star shifts along X and Y axes *after* systematic error correction. Comparison of two scans of plate D469, 1820 stars, plate rotated by 180º.**

***The residual part of constant systematic error of MICROTEK scanner does not exceed 1.5 micron.***

***DAMIAN digitizer***

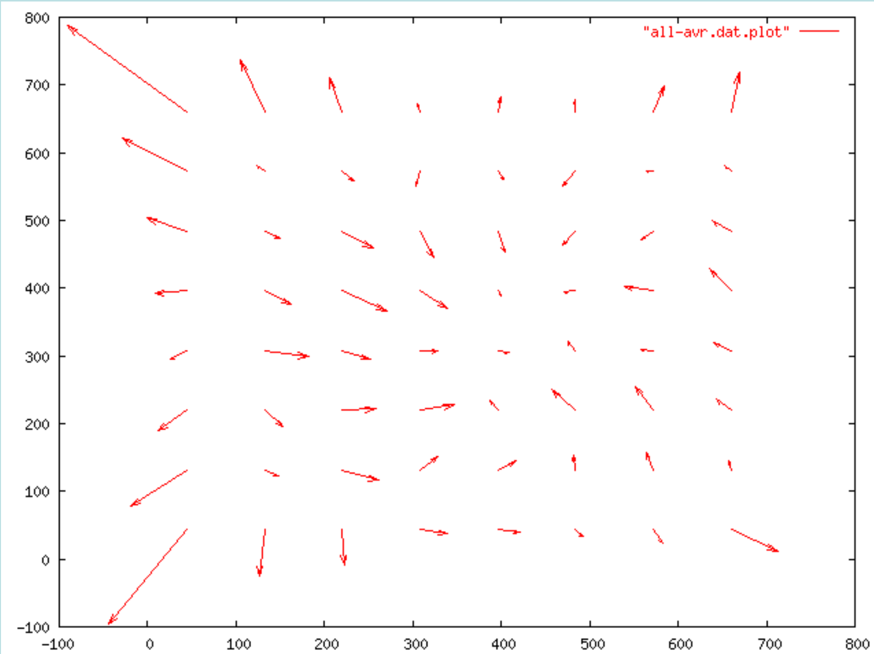



**For calibration Damian digitizer we used photographic plates with a large of quantity of stars (Pleiades). Each plate was measured at four positions with the rotation by 90 degrees.**

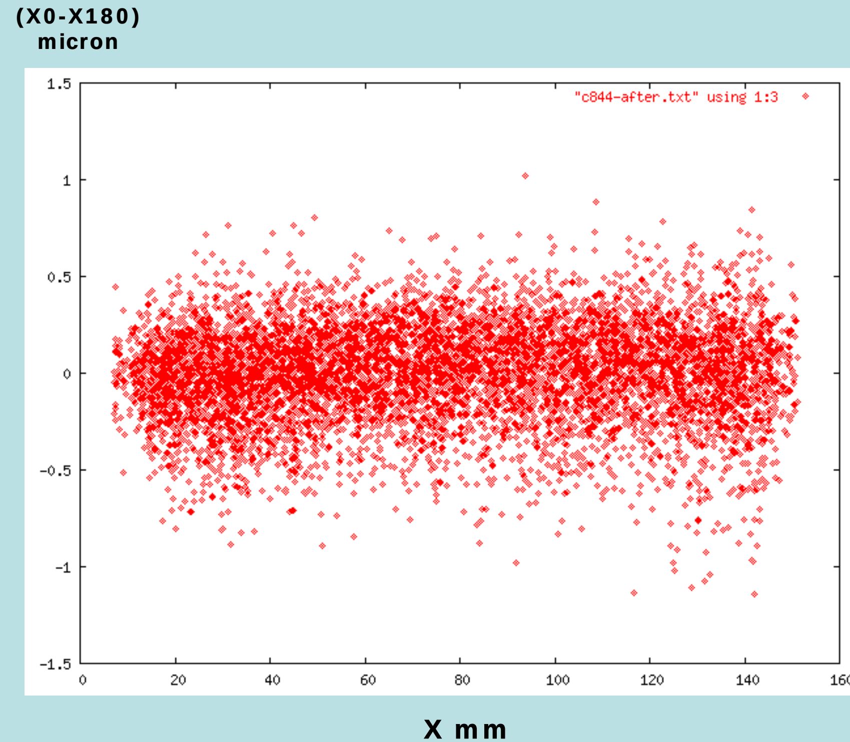
**It was been assumed that values of systematic errors and them the structure are identical in all sub-images of size 704x704 px.**

**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**




Vector diagram showing systematic error values of DAMIAN in field of size 704x704 px. The largest vectors are about 0.5 microns long .




Residual errors of measurement which obtained by comparison of two scans of one and the same plate with rotated by 180$^{o}$ after exclusion of systematic errors (plate C844, 1820 stars).

***The residuals systematic errors of DAMIAN digitizer does not exceed 0.3 micron.***

## *Method moving DOT[1]*
## *or*
## *an using the plates with stellar fields[2]*
## *for calibration?*

**The method of "moving DOT", which is used for the calibration in the ROB, allows getting the corrections which are the independent on the photographic plate. It reflects the systematic errors of the digitizing device more objectively.**

**Our corrections are tied to the quality of the plates of a certain telescope.**

**(+)** Our the calibration corrections take into consideration the sum of the scanner' errors and partially a errors of lens telescope.
**(-)** When the digitizing and the measuring the plates of other telescopes will need to obtain new corrections.


1. *Zacharias N., Winter L., Holdenried E. R., De Cuyper J. P., Rafferty T. J., Wyckoff G. L. The StarScan Plate Measuring Machine: Overview and Calibrations. // 2008. Astron. Soc. Pac., Vol. 120, p. 644-654*
2. *Khrutskaya E. V, Kalinin S.I, et.al. Use of flatbed scanner to digitize and a new reduction of photographic plates: calibration method, the measurement of coordinates, estimates of accuracy. // 2012. Izv. of Scientific Center of RAS, N 3. p. 22-38. (Russian)*

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

Each plate was scanned in four positions with rotation by 90 degree (to reduce random errors and exclusion the variable part of systematic error) by the flatbed scanner and in one position with DAMIAN digitizer.

### Further work with digitized plates included:

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

Lorentz profile was used to fit the digitized images.

**The average error of the measured coordinates (X,Y) on one plate is 0.9-1 microns for a flatbed scanner and 0.2-0.3 microns for Damian.**

# Astrometric reduction.

For the astrometric reduction the six-constant method was used.

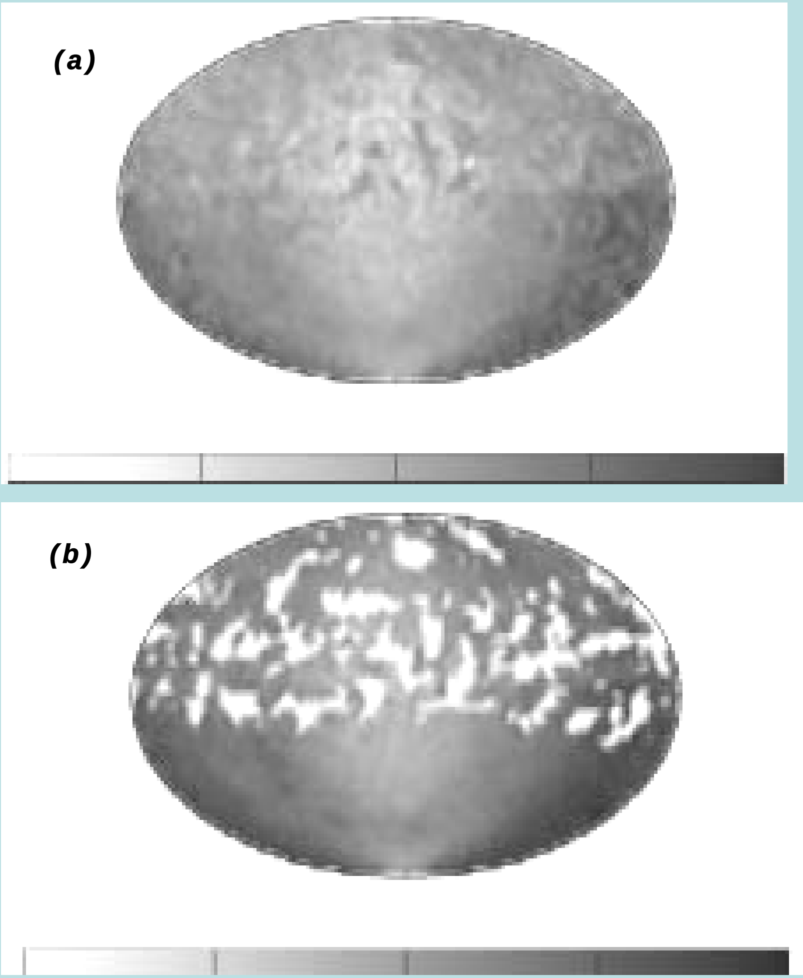
UCAC3 was used as a reference catalog.

The residual systematic errors (coma, the magnitude and color equations and so on) were taken into account.

*For the reduction we did not use the UCAC3 stars, if they satisfy the following conditions:*

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

## ***Distributions of the proper motions of UCAC3 stars in right ascension (in mas yr−1) in equatorial coordinates in the Aitoff projection for 14-15 magnitude.***




To construct these figures, we partitioned the celestial sphere into equal-area elements according to the HEALPIX scheme (Gorski et al. 2005). The mean value of $\mu_\alpha \cos\delta$ was determined in each of the 3072 elements.

**In Fig. 5a, the proper motions are present in all areas. There is a clear difference between the northern and southern hemispheres.** The small-scale in homogeneity can be said to characterize the shortcomings of the system of UCAC3 stellar proper motions pointed out by the authors of the PPMXL catalog (Roeser et al. 2010).

**Figure 5b (the number of catalogs used to derive the proper motions is more than or equal to 3)** demonstrates the absence of stellar proper motions in the above range in much of the northern sky. At the same time, the variations in proper motions with coordinates in Fig. 5b are smoother.

**This corresponds to 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 stars under consideration, Galactic rotation, and local deformation of the velocity field in Oort solar neighborhoods.**

**Fig. 5. Distributions of the proper motions of UCAC3 stars in right ascension (in mas yr−1) in equatorial coordinates in the Aitoff projection:**
**(a) without any constraint on the number of catalogs used to derive the proper motions;**
**(b) the number of catalogs is more than or equal to 3. Stars from $14^m$ to $15^m$ were used. The white color signifies the absence of proper motions.**

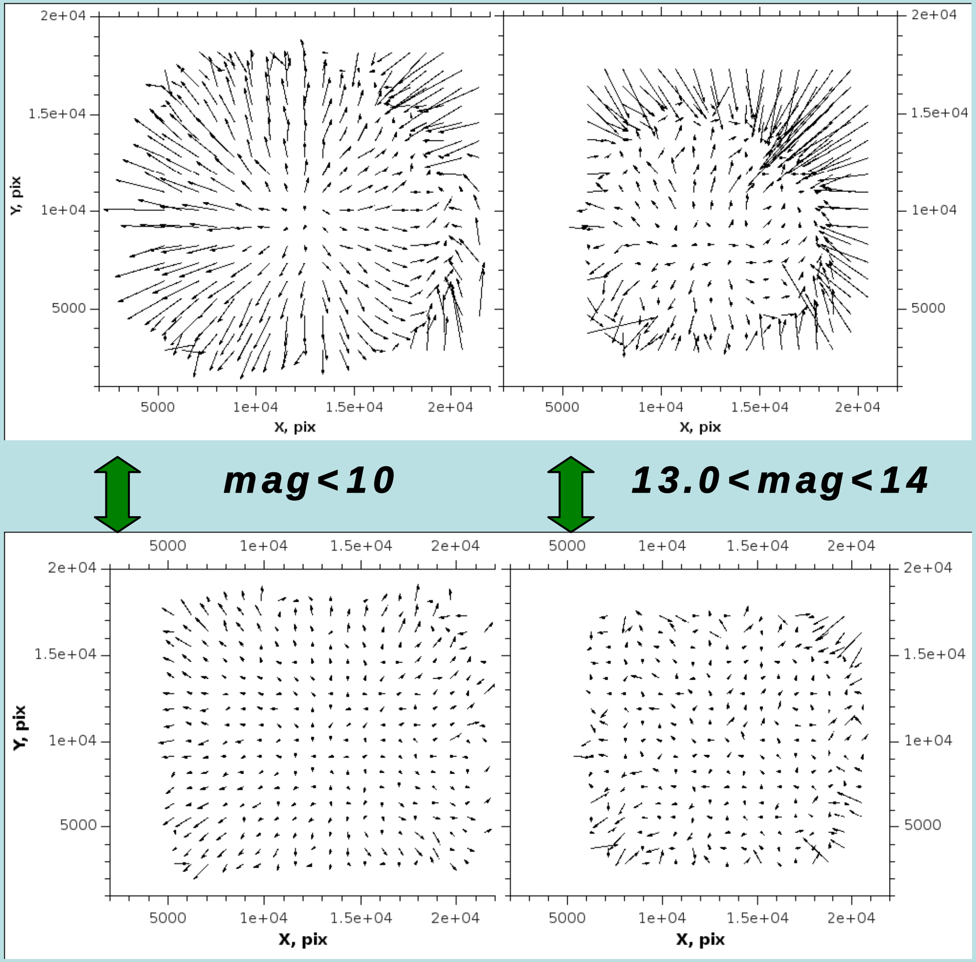
**E.V.Khrutskaya, M.Ju.Khovritchev, A.A.Berejnoy. Astronomy Letters, Vol. 37, No. 6, pp. 420–430. (2011).**
**K. M. Gorski, E. Hivon, A. J. Banday, et al., Astrophys. J. 622, 759 (2005).**
**S. Roeser, M. Demleitner, and E. Schilbach, Astron. J. 139, 2440 (2010).**

**To identify the residual systematic errors, differences of the form (O-C) of reference stars were analyzed.**

*(460000 such differences were analised for 1800 plates, which was digitized by a flatbed scanner,)*

***The vector fields of differences (O-C) for the two intervals of magnitudes.***

***before the accounting of systematic errors***




***after the accounting of systematic errors***

***The differences (O-C) include a various of errors:***

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

*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.*

# The quality of the photographic plate.

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

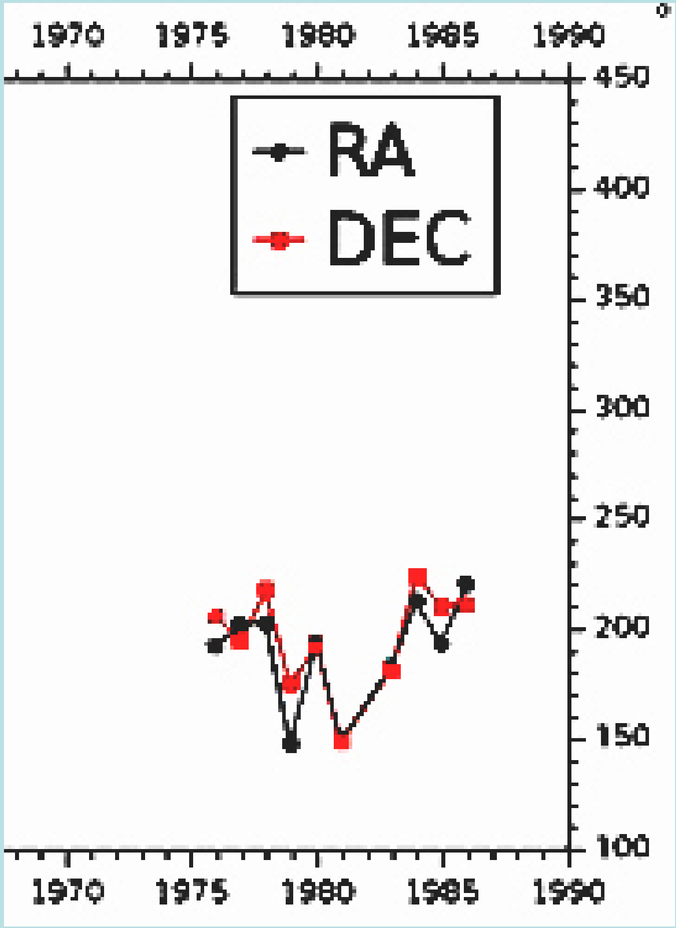
- ***State of the emulsion, grain size of the emulsion***
- ***Errors of a telescope objective,***
- ***Atmospheric conditions during the observation period.***

**It should be noted that the state of photographic emulsion varies with time. We did not make own research related to distortions in emulsion of the different photographic plates.**

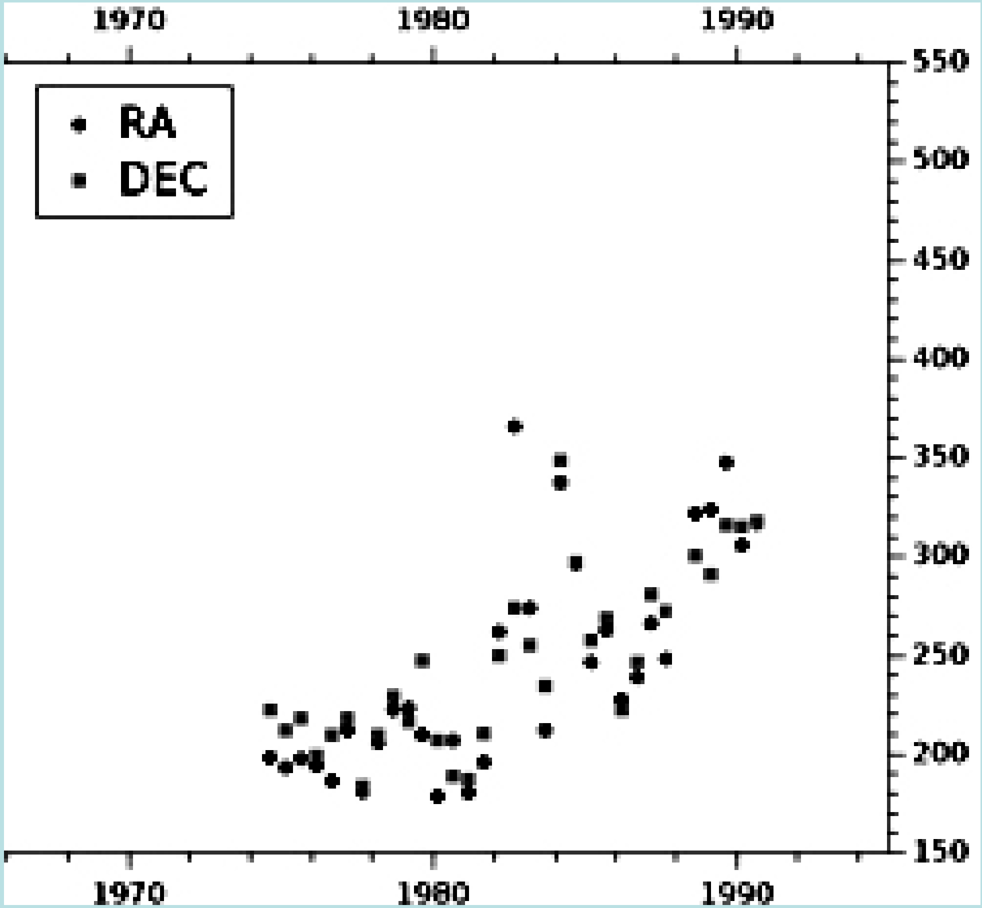
*By available researches (J.F. Lee, W. van Altena. AJ. 1983.v.88. N11; N.C.Hambly et.al. MNRAS. In 1998. V.298.p.897-904)* ***the accuracy of the digitized images is in the range 0.1 - 0.4 micron.***

**It was observed that the accuracy of determination of parameters of PSF, on the plates of good quality and on the plates with a fog is not much different, if Damian digitizer had used for digitizing. For a flatbed scanner, accuracy gets noticeably worse for plates with fog.**

## Change the values (O-C) with time for the plate digitized on a flatbed scanner and Damian.




*The digitization of photographic plates with using the Damian digitizer*




*The digitization of photographic plates with using the Microtek flatbed scanner*

***From experience with the Pulkovo plates can say:***

- ***about 10% of the plates no point digitize because of poor quality***

- ***more from 5 to 10% get into defective after reduction for different reasons:***

*- large measurement errors,*
*- errors in the metadata,*
*- loss of the object (erroneous rejection of a real object in the time of exclusion of non-stellar objects)*

*etc.*

# THE RESULTS OF NEW REDUCTION OF PULKOVO PHOTOGRAPHIC PLATES WITH SELECTED ASTEROIDS AND PLUTO USING THE DAMIAN DIGITIZER.

## *ASTEROIDS*

**167 Pulkovo photographic plates with selected asteroids were digitized using DAMIAN digitizer at Royal Observatory of Belgium (ROB)**

All plates were obtained on Normal astrograph Pulkovo Observatory in period 1949-1985. The size of the plates 160x160 mm

**Numbers of Asteroids: 1,2,3,4.6,7,11,18,39,40,532, 704**

**Magnitudes: 9 - 12**

**The average value of the standard error of the measured coordinates (X,Y) on one plate lies within 15-20 mas**

Normal Astrograph

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

**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 the same asteroids taken with ASCOREKORD (observation period 1994-1997, PPM reference catalog) was 180-200 mas***

## PLUTO OBSERVATIONS

S.G.Kostinsky

**Besides the asteroids with using the Damian digitizer was digitized 62 plates with Pluto (observations 1931-1960, mag=15.9-14.5)**

Observations of Pluto at Pulkovo were begun in March 1930 on the Normal astrograph S.G. Kostinsky.

Photographic observations of Pluto were conducted at Pulkovo up to 1994. During the period from 1930 to 1994 was obtained 272 photographic plates.

**The six-constant method, with the UCAC3 catalogue as reference, was used for the astrometric reduction**

**Mean precision of a single Pluto observations is:**
**$\varepsilon RA\cos\delta$=153 mas; $\varepsilon DECL$= 107 mas.**

*To comparing, **the accuracy** of a single observation of Pluto taken with REPSOLD meter (observation period 1930-1965) **was:***
***$\varepsilon RA\cos\delta$=260 mas, $\varepsilon DECL$= 200 mas.***
*("Precise Positions of Pluto During 1930-1965 from Photographic Observations at Pulkovo", V.V.Lavdovsky, 1968)*

## Comparison of the Pluto observations with INPOP10, INPOP8, INPOP6, EPM2008, DE421, DE405.

| | Obs. 1932-1941 (25 plates) | | | | Obs. 1949-1960 (37 plates) | | | |
|---|---|---|---|---|---|---|---|---|
| Eph | (O-C)α | (O-C)δ | σα | σδ | (O-C)α | (O-C)δ | σα | σδ |
| INPOP10 | -0”.7100 | 0”.0313 | 0”.8168 | 0”.1624 | 0”.3331 | 0”.0283 | 0”.4341 | 0”.1755 |
| INPOP8 | 1”.6502 | 0”.1276 | 1”.6843 | 0”.2166 | 0”.9083 | -0”.2246 | 0”.9336 | 0”.2863 |
| INPOP6 | -0”.9910 | -0”.1930 | 1”.0423 | 0”.2480 | -0”.8112 | -0”.1401 | 0”.8498 | 0”.2074 |
| EPM2008 | -0”.2453 | -0”.0717 | 0”.4058 | 0”.1712 | -0”.1448 | -0”.1463 | 0”.2889 | 0”.2191 |
| DE421 | 0”.0386 | -0”.0397 | 0”.3250 | 0”.1611 | 0”.0948 | -0”.1603 | 0”.2675 | 0”.2315 |
| DE405 | -0”.1769 | -0”.0172 | 0”.3686 | 0”.1574 | -0”.3758 | -0”.0751 | 0”.4517 | 0”.1747 |

To calculate the ephemeris service of IMCCE was used (http://www.imcce.fr/fr/ephemerides/generateur/.htm)

# *GAIA CATALOG*

## modern observations and old photographic observations

Both modern and old photographic observations will receive the benefit from using GAIA catalog for reduction but the extent of a benefit will differ.

### MODERN OBSERVATIONS

- The reduction of **modern CCD observations and of images out of the spacecrafts archives** will have the largest effect by the use of Gaia catalog, especially **if the subject of the study are objects fainter than 14 magnitude**. **This will be maximum a benefit with the conditional estimation *5 points*.**

- For the **ground-based CCD observations of bright planetary satellites** (5-8 mag) ***- a benefit - 3 points***

### PHOTOGRAPHIC OBSERVATIONS

- **For faint** satellites of planets and faint asteroids for objects of such as Pluto (mag>14) ***- a benefit 3-4 points.***

- **For bright satellites of planets** ( 5-8 mag), when on the plate **there are reference stars** - ***a benefit - 2 points.***

- **For bright satellites of planets** ( 5-8 mag ), when on the plate **there are no of reference stars** ***- a benefit - 1 point.***

S.Kalinin

E.Khrutskaya

A.Berezhnoy

# THANK YOU !