Long-term photographic observations for selected objects of Pulkovo program Measurements comparison and results.

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Photographical method has been applied at Pulkovo in 1874 г. during the passage of Venus along the disk of the Sun.

Such observations were made else some times and just now these have been repeated after 138 years.

The basis of development of photographic astrometry at Pulkovo have been laid by S.K.Kostinsky and have been continued by A.N.Deutsch.

Now we deal in our laboratory with plates , which have been obtained on Astrograph Carte du Ciel (since 1893 year) and on 26” refractor (since 1956).

We would like to present some history of the study of some long-term observational series on the basis of measurements by means of different measurements-devices**.**

The authors of this report have the practice of using for the same objects some old devices and also the modern machine, because the observations of these objects were continued during many years and decades with the purpose of determinations of high precision positions and movements parameters,

Prof. Alexander Nikolaevich Deutsch with his teacher, the founder of a Department of Photographic Astrometry in Pulkovo, member-correspondent of the Academy of sciences **Sergey Konstantinovich Kostinsky.**

We will consider some series of double and single stars, which were of interest for researchers by peculiarities of their motion, dynamics, their origin and of the belonging to different stellar systems.

As a rule these are stars located near to the Sun. Some of them are interesting and perspective objects for the future space missions with the purpose of detection of planetary components.

In connection with it their inner structure and processes observed on their surface also in the center of attention of many specialists.

Some of them, for instance, **61 Cygni (ADS 14636)** and **ADS 7251** are entered in **NASA STAR and Exoplanets Datebase** as very important objects- **Tier target stars)** for observations in the future during space mission

D=65 cm F=10.4 m
M=19.814"/mm

D=34 cm F=3.4 m
M=59.56"/mm

1)

Blink-comparator

1900-1960

2)

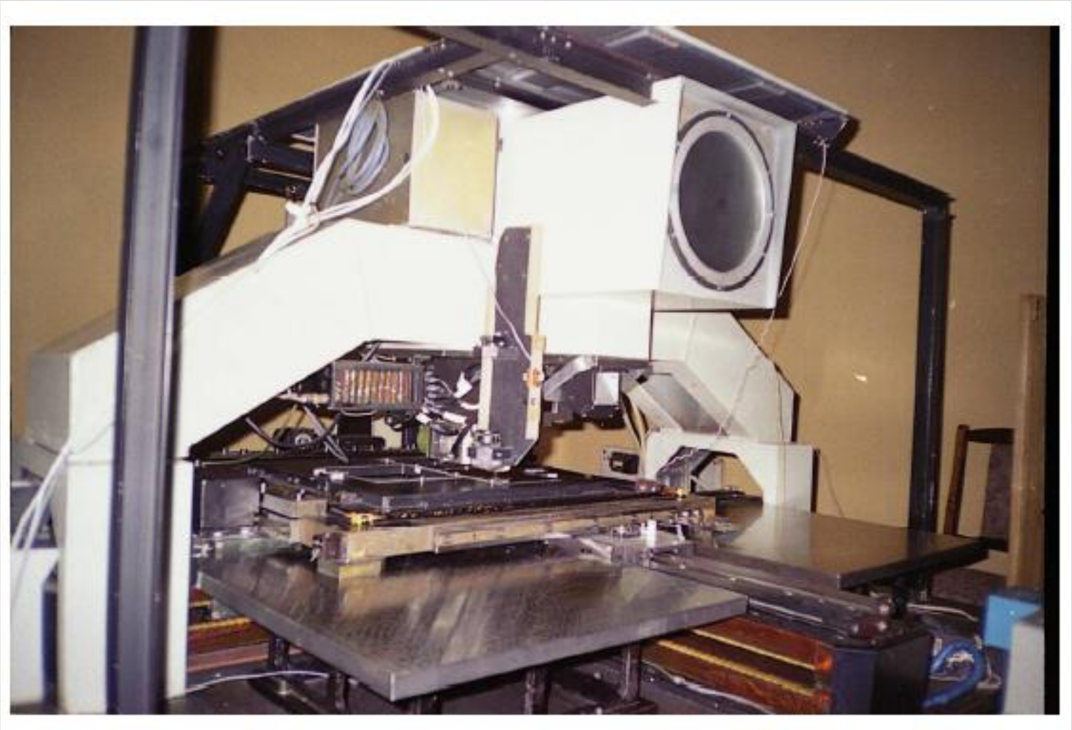
The sheme of semi-automatic machine "Ascorecord"

1972-2005

3)

Automatic coordinate - measuring machine with photoelectric positioning system for purposes of astronomy designed by **L.M. Zatsiorsky at Pulkovo** in **1974.**

4)



The Pulkovo Astrographic Measuring Machine (PAMM)
E.V.Poliakow, Pulkovo, 1986.

Открытие невидимого спутника можно рассматривать как подтверждение существования новых планетных систем.

Масса темного спутника 61-й Лебедя — это самая малая из известных звездных масс. Можно считать, что темный спутник является промежуточным звеном между звездами и планетами.

Целью дипломной работы было исследование точности измерения расстояний между компонентами 61-й Лебедя на пластинках, полученных на 26-ти дюймовом рефракторе и нормальном астрографе Пулковской обсерватории. (1958г.)

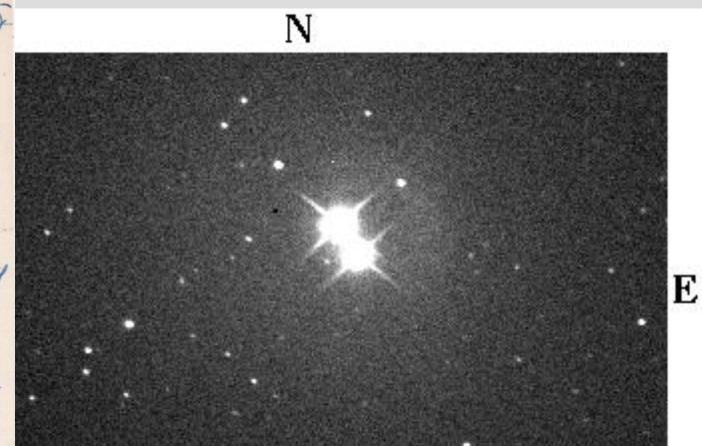
Экваториальные координаты 61 Лебедя: $\{ \alpha = 21^h 04^m,5 ;\ \delta = +38°29'$

В следующей таблице дается описание пластинок: Agfa несенсибил.

Таблица 1а

Пластинки, снятые на нормальном астрографе

№ пластинки	Дата	экспозиция	
5970	30/31-VIII-58г.	9 изображений по 1 минуте	
5971	31-VIII-1-IX-58г.	"	
5972		"	
5974	2/3-IX-58г.	"	
5975	2/3-IX-58г.	"	
5999	15/16-IX-58г.	"	
6004	17/18-IX-58г.	"	



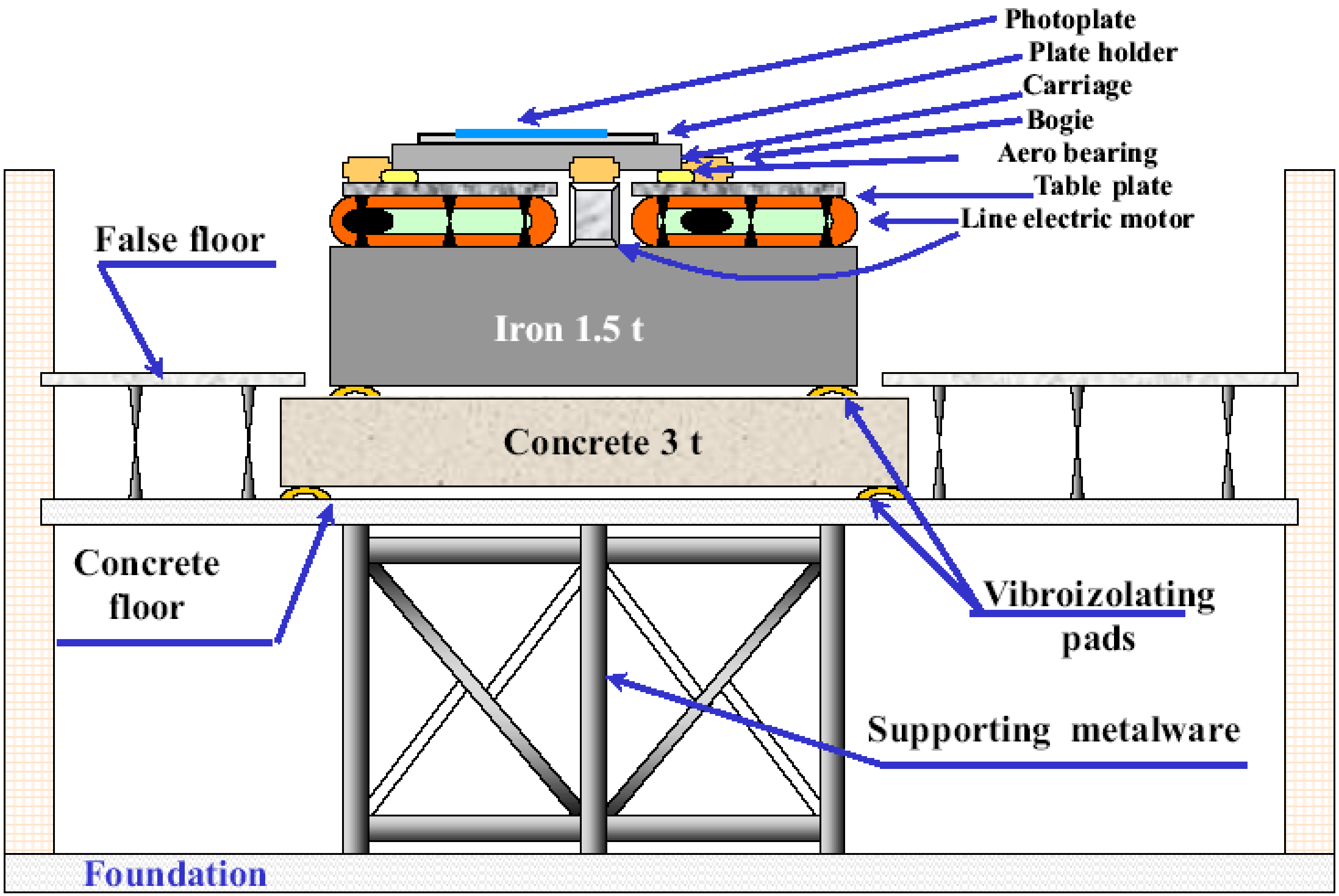
...следующей таблице даются вместе ...средними расстояниями вероятные ...бки для одной пластинки и для ...пластинок:

Таблица 3.

	Рср.	ϰ	ε	Рвак.	ϰ''	ε''
	6.816	±0.005	±0.002	27".380	±0".020	±0".008
	2.265	0.002	0.001	27".392	0".024	0".012

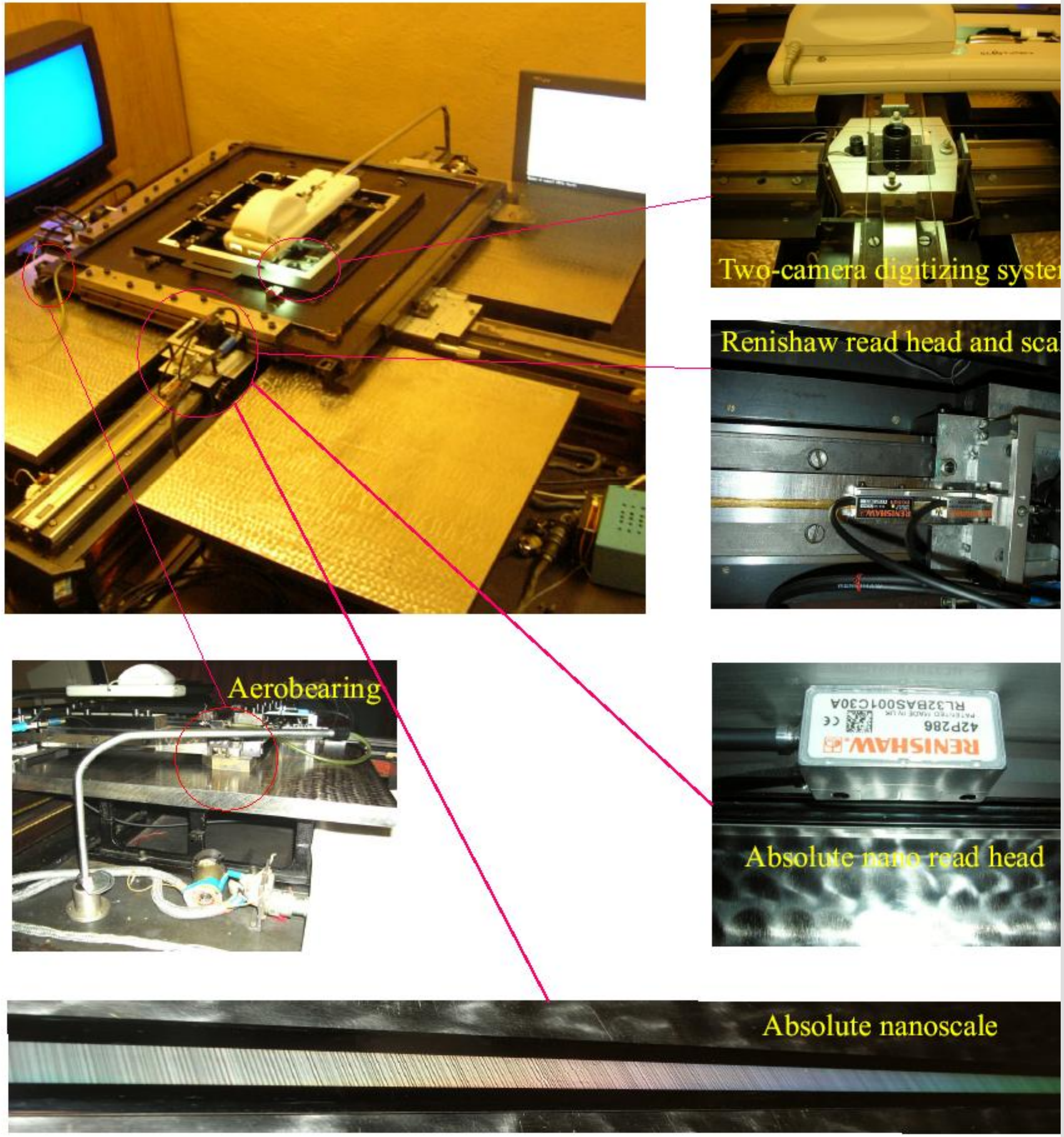
...всех пластинок вычислены личные ...бки наведения по координате X ...формуле $\varepsilon = 0.4247 \frac{\Sigma \Delta}{n-1}$, где n число ...бражений, а Δ - разности расстояний ... для каждого изображения при ...воначальном положении пластин- ... и при повороте на 180°.

Scheme of the PAMM structure and installation



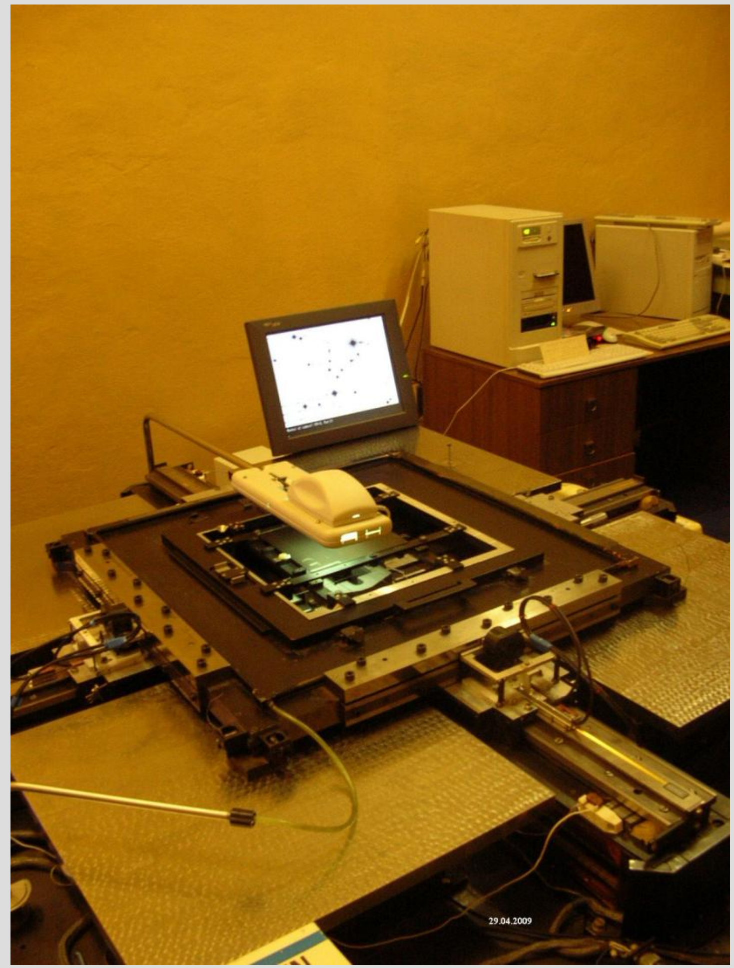
5)

Fig. 2. PAMM after reconstructon in 2005 year.

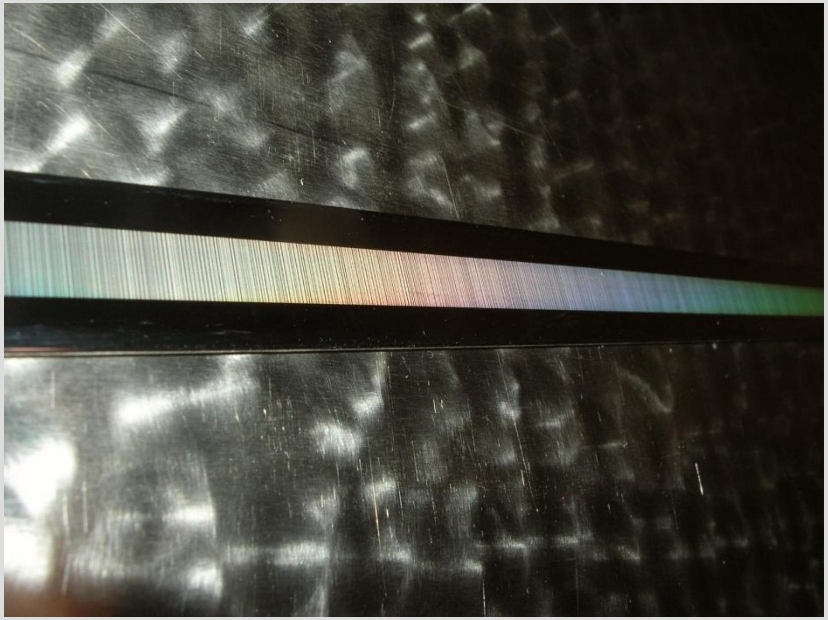


1. The beginning of reconstruction

Camera WAT, 1.7x 1.2 mm
px: 2.88x 5.00 mμ



New camera 6.4x4.8 mm, px: 3x3 mμ



Absolute nanoscale

Some technical details

Description of Positioning System of automatic machine “Fantasy”

The mobile part of the unit is a steel carriage with high precision orthogonal guide rails fastened to both sides.

The carriage is propelled by 2 linear electric motors; it moves on air bearings having 5-7 micron air gap above a table consisting of four plates measuring 500 x 500 mm each.

The plates are made of non-magnetic stainless steel. A duralumin holder for photoplates is fastened to the carriage.
The carriage is moved an its position is measured with the help of a positioning system.

The positioning system based on **RGH24** and **RGH25** miniature positional contactless **encoders** and **RGF0200H** interpolators made by the **Renishaw** company.

The system of scanning of automatic machine "Fantasy"

The system of scanning includes two cameras:

1) overview **CCD** camera **WAT-704** with a field of vision 60x40 мм^2

2) measuring camera **EVS-535** with a field 6x4 мм^2.

Both cameras are built in the uniform duraluminium platform established in the center of a table under the gaffer 80x60 мм^2 .

The overview camera is intended for an identification of a plate with the catalogue and bindings of system of coordinates of a plate to system of the measuring machine.

By means of the measuring's camera is carried out the digitizing of a photographic plate continuously or for the selected fragments of the image.

Calculations of relative positions of double stars components.

$$X = M_0 X(1+\beta(1+k_1^2)) + M_0 Y(2\beta k_1 k_2 + \gamma)$$

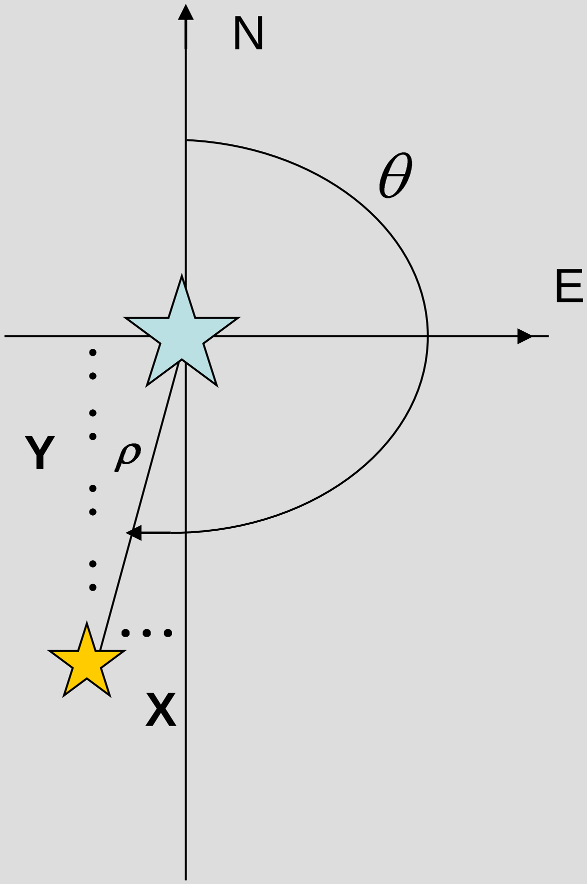
$$Y = M_0 Y(1+\beta(1+k_2^2)) - M_0 X\gamma$$

$$\rho = \sqrt{X^2 + Y^2} \qquad \mathrm{tg}\,\theta = \frac{X}{Y}$$

$$\sigma_\rho = \sqrt{\sigma_X^2 \sin^2\theta + \sigma_Y^2 \cos^2\theta}$$

$$\sigma_\theta = \frac{1}{\rho}\sqrt{\sigma_X^2 \cos^2\theta + \sigma_Y^2 \sin^2\theta}$$

$$X_{2000} = \rho \sin \theta_{2000}, \qquad Y_{2000} = \rho \cos \theta_{2000}.$$



How should be generally estimated the accuracy of measurements?

How errors of measurements were calculated?

I. Small field: relative positions of double stars components.

II. Wide field: object and reference stars.

I. Small field: relative positions of double stars components

n **- the number of images on a plate; *N* - the number of plates in a year;**

v **- the deviation from mean image on one plate;**

V **- the deviation from one mean yearly position.**

1) The error of **one image** (exposure): $\sigma_1 = \sqrt{\dfrac{vv}{(n-1)}}$

2) The **inner** error of **one plate**: $\sigma_i = \dfrac{\sigma_1}{\sqrt{n}}$

3) The **external** error of **one plate**: $\sigma_e = \sqrt{\dfrac{VV}{N-1}}$

4) Error of mean **annual normal place:** $\sigma_a = \sqrt{\dfrac{VV}{N(N-1)}}$

5) the **error of the night** of observations: $\sigma_n = \sqrt{(\sigma_e)^2 - (\sigma_i)^2}$

The first experience of measurements with **Zatsiorsky automatic machine at Pulkovo in 1974**.

The 16 plates of 26” refractor with the star ADS 7251 have been used.

ADS 7251	Automat	Blink-comparator	Ascorecord
σ1x	3.4 μm (0.”068)	3.1 μm (0.”062)	2.6 μm (0.”052)
σ1y	3.2 (0.064)	2.9 (0.058)	2.6 (0.052)
σix	1.0 (0.020)	0.8 (0.016)	0.7 (0.014)
σiy	0.9 (0.018)	0.7 (0.014)	0.7 (0.014)
σax	0 ”.022	0 ”.014	0”.008
σay	0”.028	0 ”.020	0”.009

$\sigma 1_{xy}$ – error of one image; n – the number of images; **n=16**

σ_{ix} – error of one plate; σ_{ax} - error of mean annual place;

N - the number of plates in one year; **N= 4**

Comparison of the accuracy of ADS 11632 measurements

	X (Ascor)	Y (Ascor)	X (Fant)	Y (Fant)
σ_{1xy}	3.4 μm 68 mas	4.1 μm 82 mas	1.8 μm 36 mas	2.3 μm 46 mas
σ_{ixy} inner	1.1 21	1.3 25	0.6 11	0.7 14
σ_{exy} out	1.5 29	2.2 43	0.9 18	1.5 29
σ_n night	1.0 20	1.8 35	0.7 14	1.3 25
σ_a	0.7 13	0.9 18	0.4 8	0.7 13

Selected stars for measurements, processing and comparison.

N	Name	π	σ_{axy}	ΔT Time	N plates	Remarks
1	ADS 5983 (δ Gem)	0".064	0."020	27	104	Ascor
2	ADS 7251	0.163	0.006 /0.004	43	200	Ascor /Fant
3	Lal 21185*	0.397	0.016	33	93	Ascor
4	Gliese 623*	0.124	0.011 /0.007	17	89	Ascor /Fant
5	ADS 11632	0.282	0.016 /0.011	36	176	Ascor /Fant
6	ADS 14636 (61 Cyg)	0.287	0.007 -26"ref 0.008 -CdC	50 100 years	350 -26" 800 -CdC plates	Ascor /Fant (2 series of observations)
7	ADS 14710 *control*	0.002	0.008	21	170	Fant
8	51 Peg*	0.074	0.010	8	40	Fant

Accuracy of measurements. Single stars.

Name	Z	σ_{1xy} (error of one image)	$\sigma_{i\ xy}$ (inner error of a plate)	σw_{xy} (error of unit of the weight)	σ_a (annual error)	ΔT [years]
Lalande 21185 (Ascor)	24°	0".044 2.2 µm	0".020 1.0 µm	0".036 1.8 µm	0".014 0.7 µm	32
Gliese 623 (Ascor)	12°	0 ".038 1.9 µm	0".017 0.9 µm	0". 042 / 0." 036 2.1/ 1.8 µm ***	0". 011 0. 6 µm	17
Gliese 623 (Fant)		0". 028 1.4 µm	0 ". 012 0.6 µm	0". 038 / 0 ". 033 1.9 / 1/7 µm ***	0 ". 007 0. 4 µm	17
51 Peg (Fant)	39°	0". 034 1.7 µm	0". 016 0.8 µm	0". 031 1.6 µm	0". 010 0.5 µm	8

*** - The errors are shown before the excluding of orbital motion of photocenter and after its excluding.

Accuracy of measurements. Double stars.

Name ADS	Z	ρ	Δm	σ_{1xy} one image	σ_{ixy} one plate inner	σ_{axy} annual	$\sigma_{a(\rho)}$ annual rho	$\sigma_{a\,(\theta)}$
5983 (δ Gem) Ascor	38°	6"	$4^m.8$	0".072 3.6 μm	0".020 1.0 μm	0".018	0".020	0°.03
7251 Ascor	7°	17”	0.1	0.052 2.6	0.014 0.7	0.007	0.006	0.03
Fant				0.032 1.6	0.008 0.4	0.005	0.004	0.02
11632 Ascor	0°	14"	0.8	0.075 3.8	0.022 1.1	0.016	0.014	0.04
Fant				0.042 2.1	0.012 0.6	0.011	0.012	0.03
14634 (61 Cyg) Fant	2°	30”	0.7	0.028 1.4	0.007 0.4	0.007	0.007	0.03

Wide field: object and reference stars.

The estimations of errors of object and relative stars.

I . The errors of one image:

$$\sigma_{x1} = \sqrt{\frac{1}{m-3}\sum_{i=1}^{m} \Delta x_i^2}\,, \qquad \sigma_{y1} = \sqrt{\frac{1}{m-3}\sum_{i=1}^{m} \Delta y_i^2}$$

II. Errors of one plate (inner):

$$\sigma_{x\mathrm{AMC}} = \frac{\sigma_{x1}}{\sqrt{m}}\,, \qquad \sigma_{y\mathrm{AMC}} = \frac{\sigma_{y1}}{\sqrt{m}}$$

Wide field: object and reference stars.

$$X_j = C_x + \mu_x (t_j - t_o) + \pi P_x$$

$$Y_j = C_y + \mu_y (t_j - t_o) + \pi P_y$$

Solution of equations by means of least squares method.

$$X_1 = C_x + \mu_x (t_1 - t_o) + \pi P_x$$

$$X_2 = C_x + \mu_x (t_2 - t_o) + \pi P_x$$

....

$$X_n = C_x + \mu_x (t_n - t_o) + \pi P_x$$

Residuals *O - C*

$$X_{obs1} - X_{calc1} = V_1$$

$$X_{obs2} - X_{calc2} = V_2$$

....

$$X_{obs\,n} - X_{calc\,n} = V_n$$

III. Error of the unit of weight :

(outer error of one plate)

$$\sigma_w = \sqrt{\frac{VV}{n - m}}$$

IV. Error of mean yearly normal place.

This error is calculated with taking into account residuals of individual plates within on year.

$$\sigma_a = \sqrt{\frac{VV}{N - 1}}$$

Wide field: a single star + reference stars

V. The error of the reduction.

$$\sigma_r = \sqrt{\sigma^2_m + \sigma^2_\mu (\Delta t)^2}$$

The error of reduction σ_r increases with the difference of epoques

$\sigma_\mu = \Sigma(\mu_i D_i + \Delta \mu_i)$

For calculation of error of measurement of relative stars the difference of the moments Δt must be no more 1 year. We neglect of the second composed and received **the error of one image for the "mean" star.**

For instance, **for Gliese 623 with** $\Delta t = 0$:

Visual σ_m: **2.1** μm and **2.4** μm for **X, Y** accordingly **(0".045)**

Automatic σ_m μm and μm for **X, Y** accordingly **(0".038)**

Additional problem: the influence of a known or unknown optically unseen companion.

$$X_j = C_x + \mu_x (t_j - t_o) + \pi P_x - B \Delta X$$

$$Y_j = C_y + \mu_y (t_j - t_o) + \pi P_y - B \Delta Y$$

$$\Delta X = \mathrm{B} x + \mathrm{G} y$$

$$\Delta Y = \mathrm{A} x + \mathrm{F} y$$

$$x = \cos E - e \qquad y = \sin E \sqrt{1 - e}$$

$B = M2/(M1+M2)$

The consequence is : deviation in the stellar path,

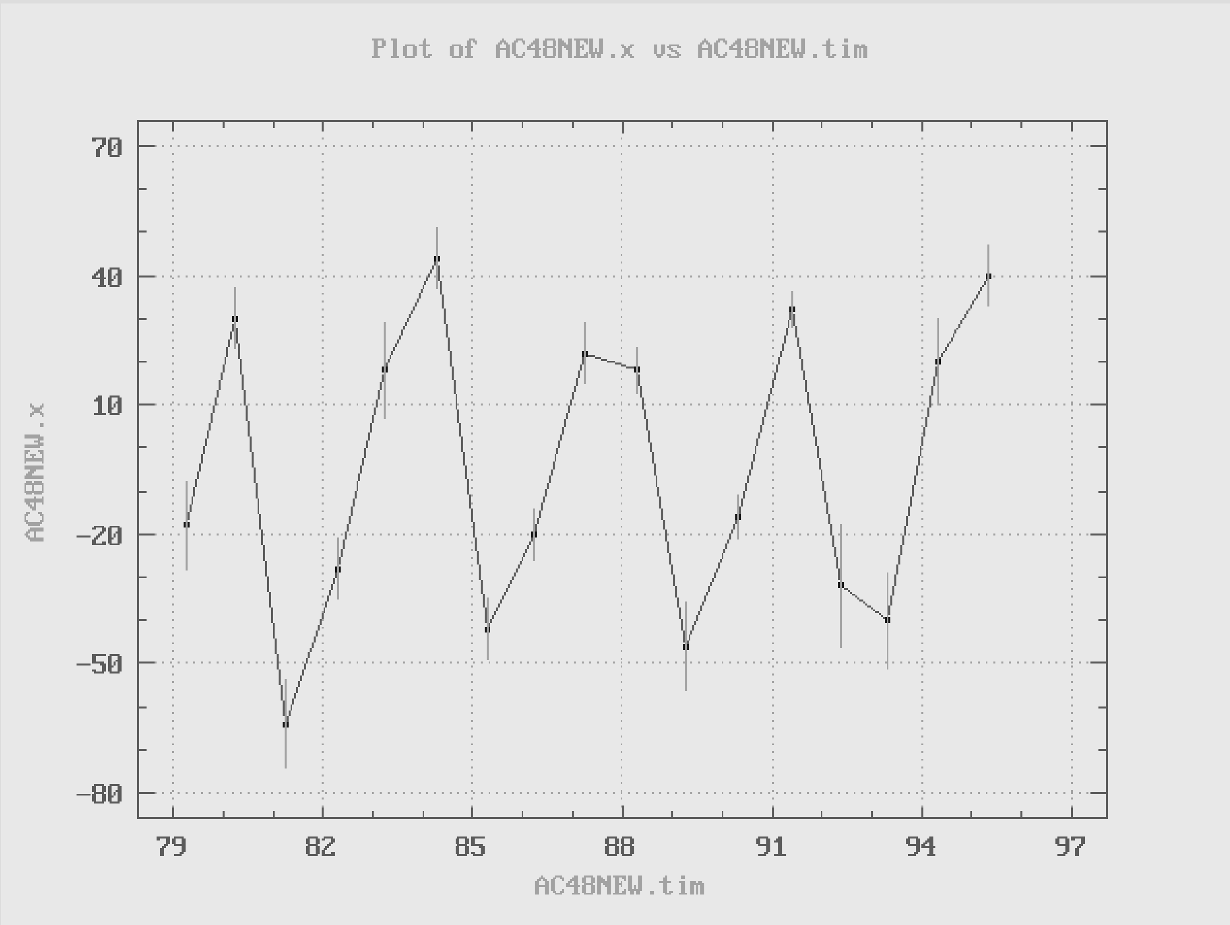
increasing of σ_w - **units weight error** and errors of all parameters .

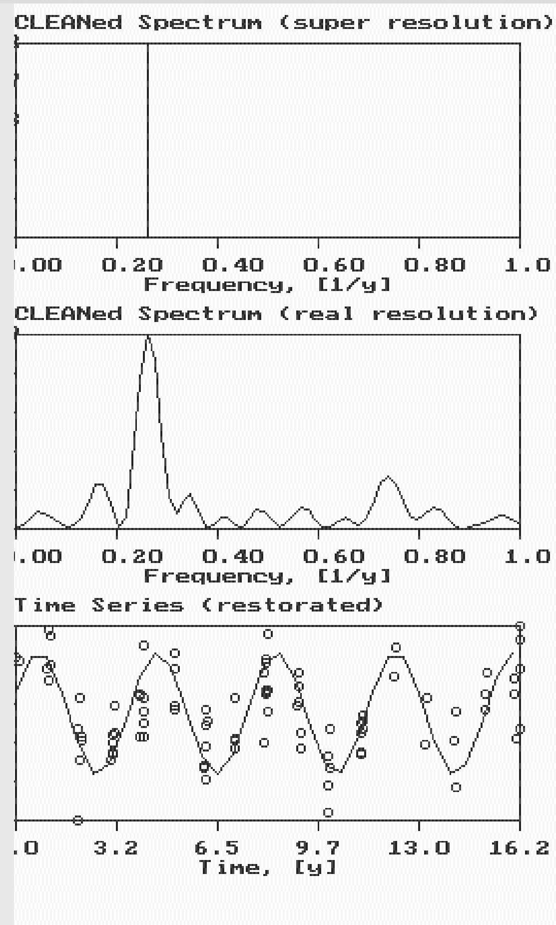
The sample: Gliese 623.

Error of units of weight σ_w = **0”042 (Ascorecord)** and **0”.038 (Fantasy)**

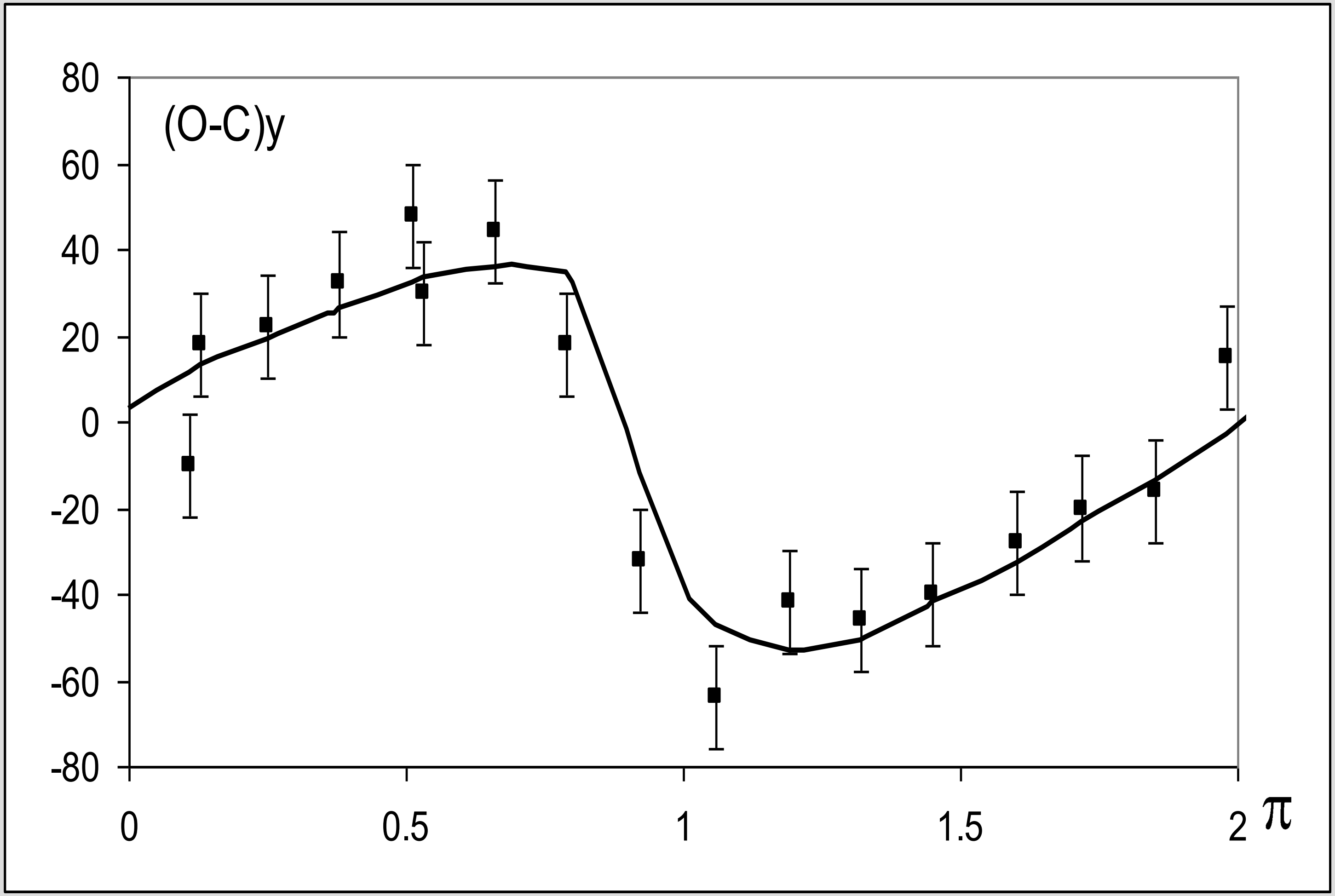
After the exception of the **influence of satellite**

σ_w = **0”.036 (Ascorecord)** and **0”.033 (Fantasy)**



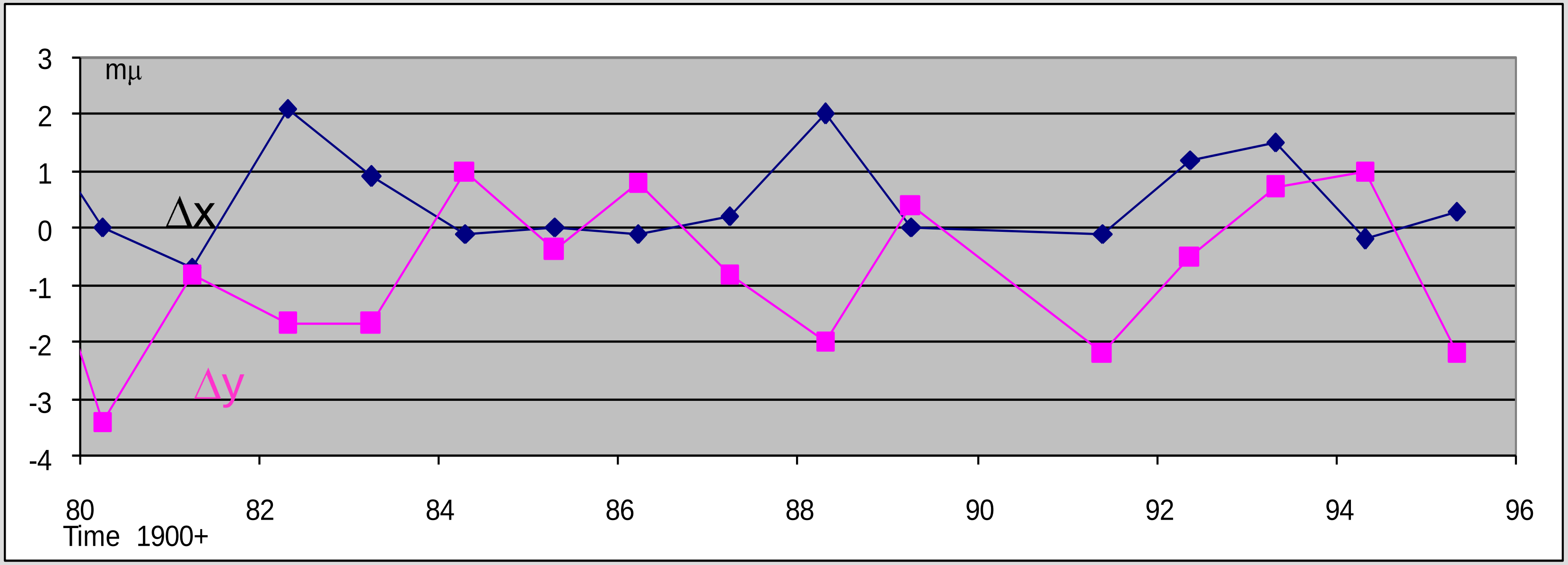


Periodic deviations from rectilinear movement of the photocenter of systemGliese 623A + Gliese 623B



Periodic deviations from rectilinear movement of the photocenter of system Gliese 623A + Gliese 623B, received in Pulkovo and caused by an attraction of the optically invisible satellite with mass 0.098 solar masses and with period 3.76 years .

On the abscisses axis a phase angle is shown, on an axis of ordinates - the periodic displacement (O-C)y **in milliseconds** in a projection on RA .

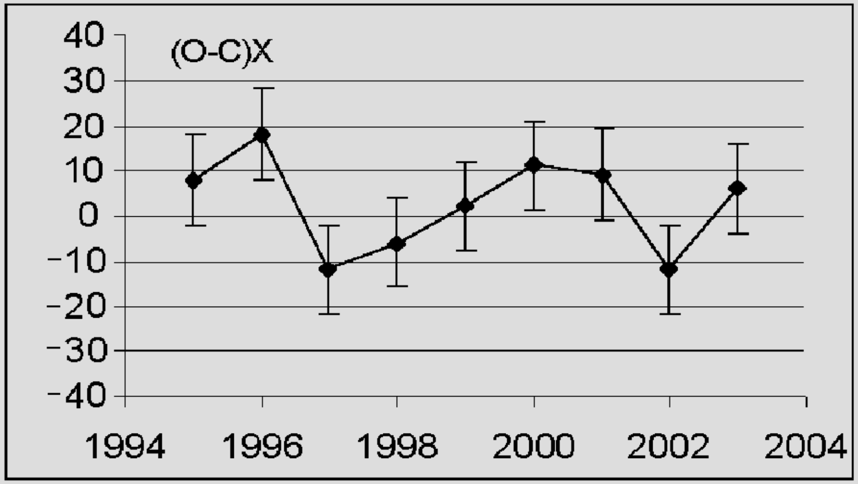


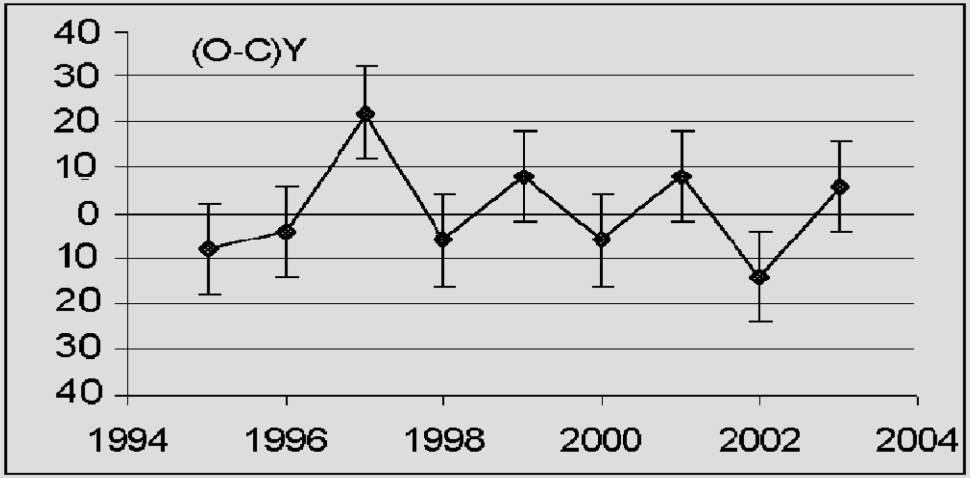
The differences Ascorecord – “Fantasy” for Gliese 623
(AC48º 1595/1589) in mean positions on RA projection.

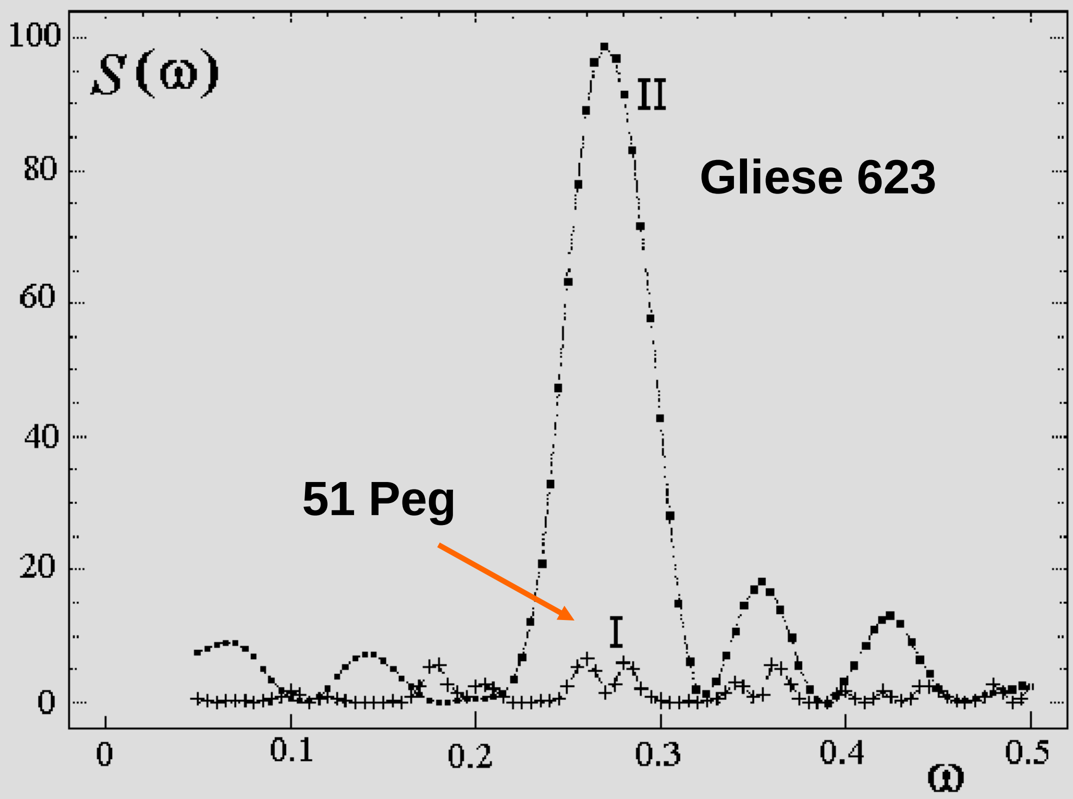
Systematic differences in separations of double stars have been revealed:

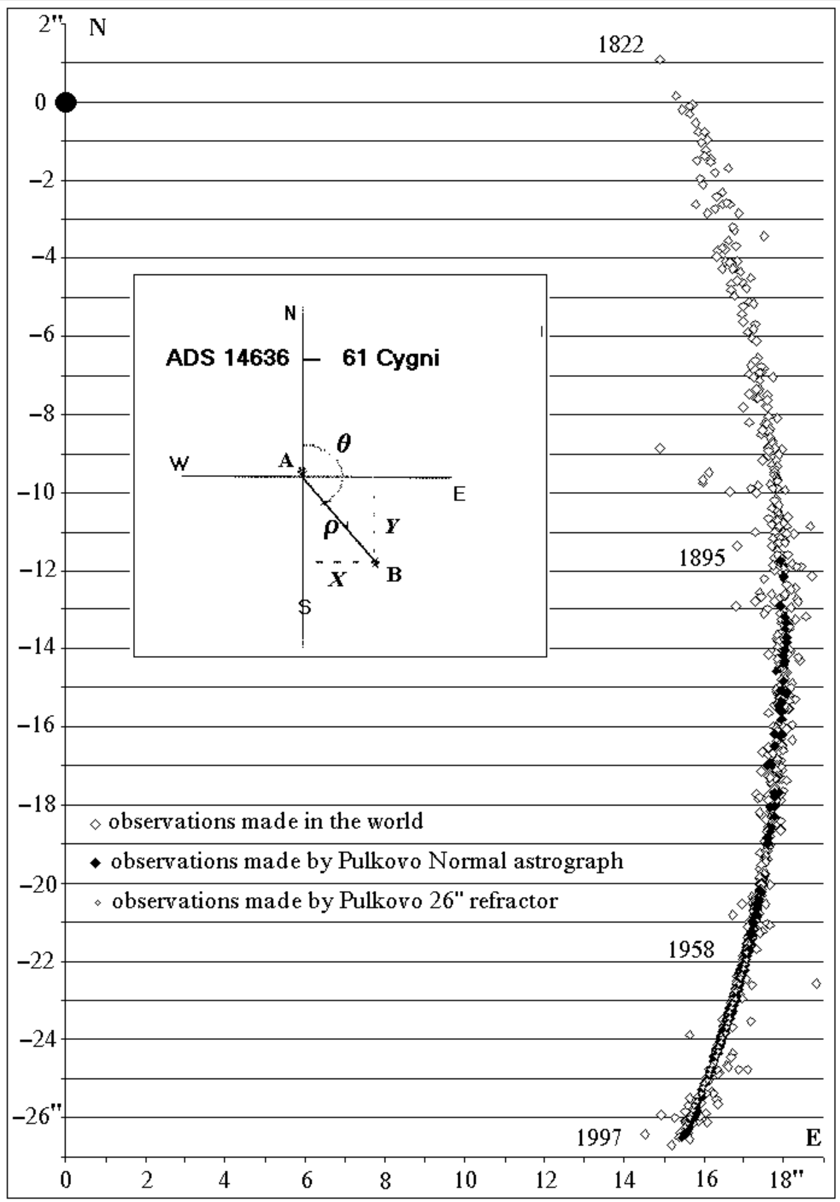
Visual-auto	0."030	0.004	for ADS 11632
	0.018	0.004	for ADS 7251
	0.048	0.004	for ADS 14636

51 Peg

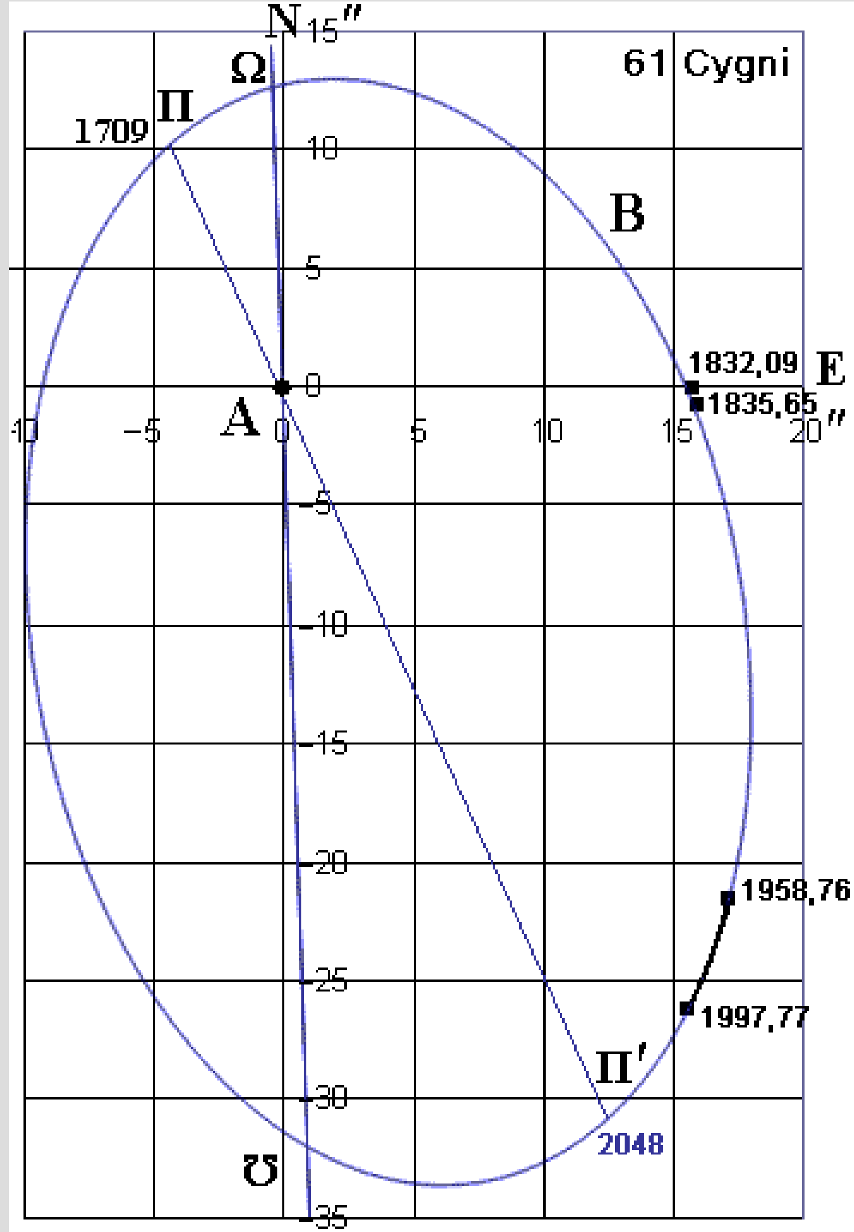

(O-C)X
40
30
20
10
0
−10
−20
−30
−40
1994
1996
1998
2000
2002
2004


(O-C)Y
40
30
20
10
0
10
20
30
40
1994
1996
1998
2000
2002
2004


S(ω)
100
80
60
40
20
0
II
I
Gliese 623
51 Peg
0
0.1
0.2
0.3
0.4
0.5
ω



N
E
1822
1895
1958
1997
ADS 14636 — 61 Cygni
N
W
E
S
A
B
θ
ρ
X
Y
◇ observations made in the world
◆ observations made by Pulkovo Normal astrograph
◇ observations made by Pulkovo 26" refractor
2"
0
−2
−4
−6
−8
−10
−12
−14
−16
−18
−20
−22
−24
−26"
0
2
4
6
8
10
12
14
16
18"



61 Cygni
N
E
A
B
Ω
Π
Π′
℧
1709
1832,09
1835,65
1958,76
1997,77
2048
15″
10
5
0
−5
−10
−15
−20
−25
−30
−35
−10
−5
0
5
10
15
20″

Orbit and mass estimation of 61 Cygni

- **61 Cyg**
- **semi-axis major** — a = 82.2 ± 2 a.u.
- **excentricity** — e = 0.49 ± 0.03
- **inclination** — i = 129º ± 2º
- **longitude of periastron** — ω = 149.5º ± 6º
- **P.A. of ascending node** — Ω = 178º 4 ± 2º
- **period** — P = 678 ± 34
- **epoch of periastron passage** — T_o = 1709 ± 16

- **Comparison with ephemeris (Pulkovo)** — **Comparison with CCD-observations**

Ephemeris (Pulkovo) $(O-C)\rho$	Ephemeris (Pulkovo) $(O-C)\theta$	CCD-observations $(O-C)\rho$	CCD-observations $(O-C)\theta$
0."007	0.º01	0".024	0º.05

$M_A = 0.71 \quad 0.10 M_\odot \; ; \quad M_B = 0.49 \quad 0.07 M_\odot .$

Comparison of visual (Ascorecord) and automatic ("Fantasy")measurements

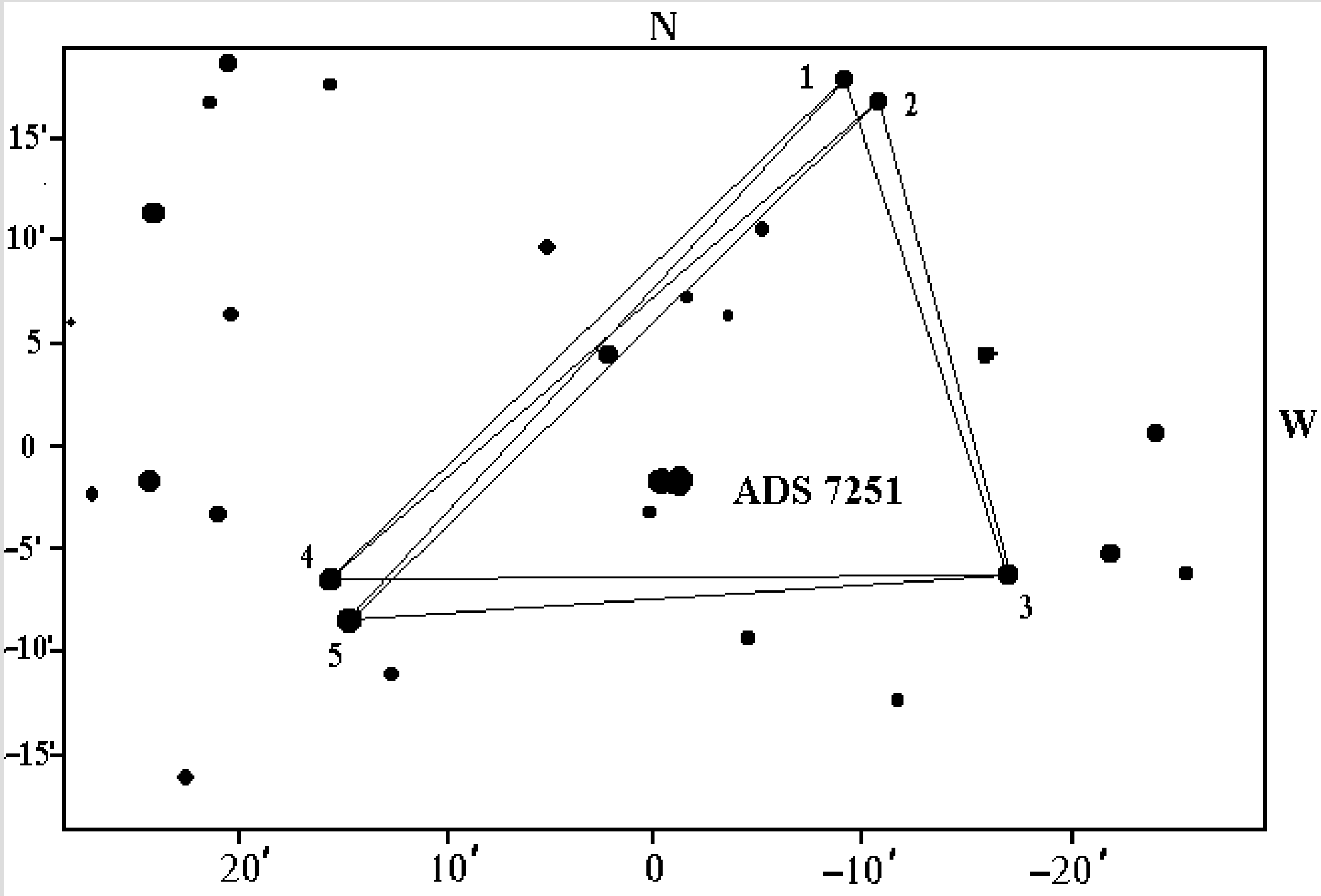
Orbit of photocenter Gliese 623.

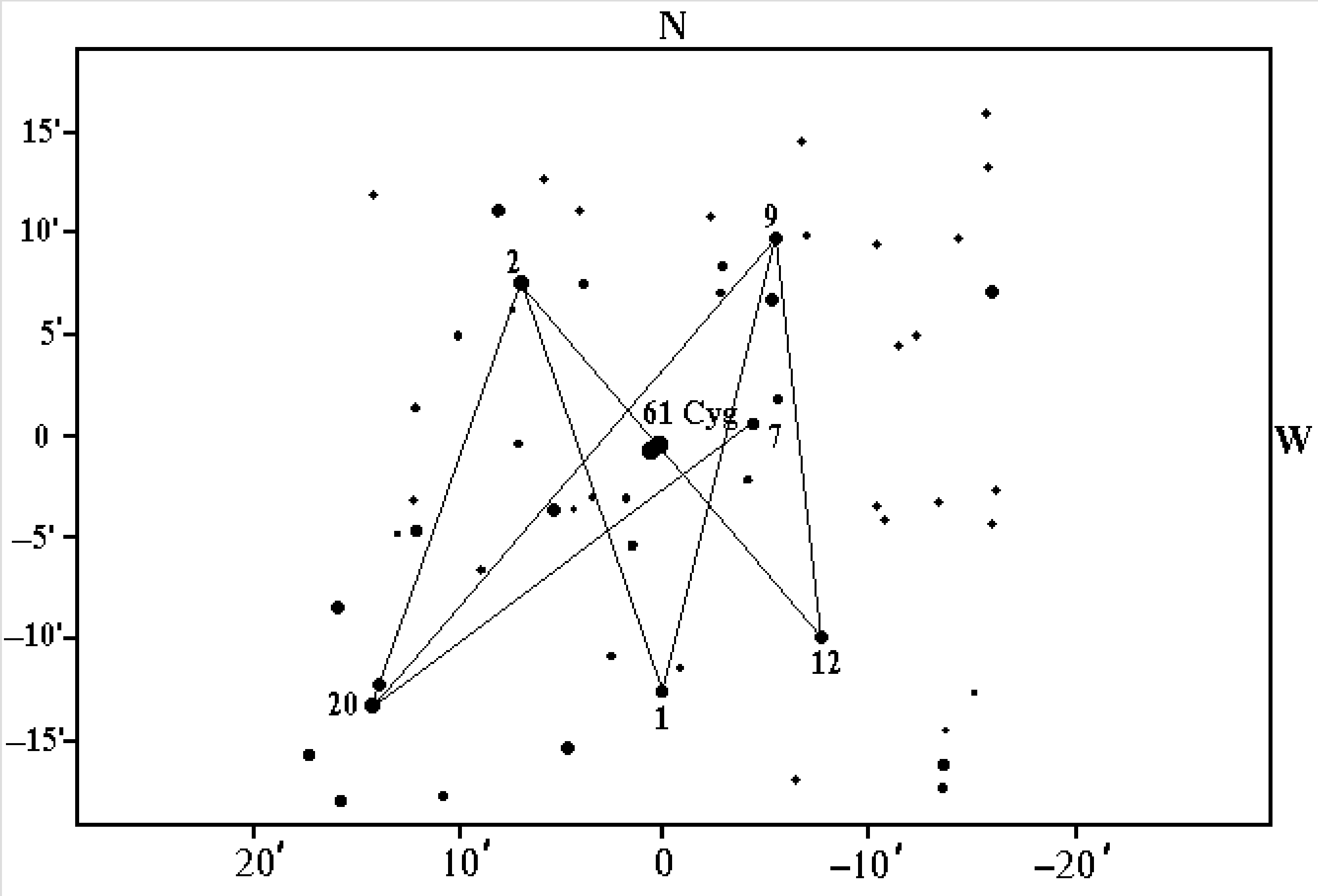
semi-axis major	a =	0".053	0."006	0.053
excentricity	e =	0.51	0.03	0.51
inclination	i =	141°	5 °	141
longitude of periastron	ω =	289°	10 °	265
P.A. of ascending node	Ω =	149°	10 °	126
Period	P =	$3.^{yr}76$	0.10	3.76
epoch of periastron passage	To =	$1984^{yr}.3$	10	$1984^{yr}.3$

- The low limit of the mass of unseen satellite 0.09 0.03 Solar masses.

Orbit of double star ADS 11632

semi-axis major	a =	27".3	26".7
excentricity	e =	0.43	0.42
inclination	i =	$106^{o}.6$	$106^{o}.7$
longitude of periastron	ω =	$318^{o}.4$	$318^{o}.9$
P.A. of ascending node	Ω =	$145^{o}.0$	$145^{o}.2$
period	P =	$1124^{yr}.4$	$1092^{yr}.7$
epoch of periastron passage	To =	$1834^{yr}.2$	$1835^{yr}.9$


N
W
15'
10'
5
0
-5'
-10'
-15'
20′
10′
0
−10′
−20′
1
2
3
4
5
ADS 7251



N
W
15'
10'
5'
0
–5'
–10'
–15'
20′
10′
0
–10′
–20′
61 Cyg
2
9
7
12
20
1

Calculation of geometrical scale *Mo* .

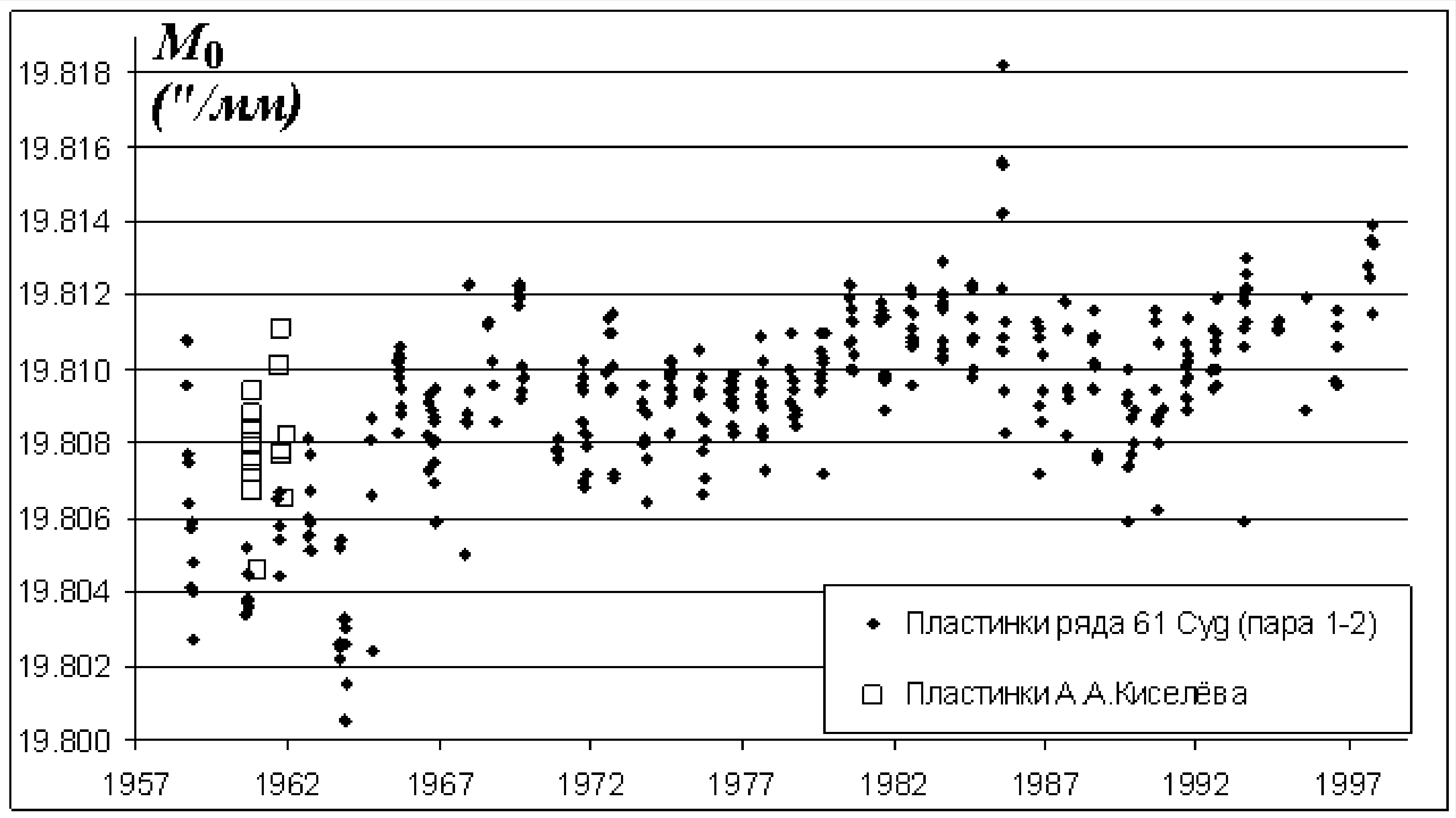
$$M_0 = \frac{1}{F}$$

$$\Delta\sigma_* = \Delta\sigma_1 - 0.0457'' \frac{\left(\Delta\alpha^{(\circ)} \cos\bar{\delta}\right)^2}{\Delta\sigma_1^{(\circ)}} \left[\left(\Delta\alpha^{(\circ)} \sin\bar{\delta}\right)^2 + \left(\Delta\delta^{(\circ)}\right)^2 \right]$$

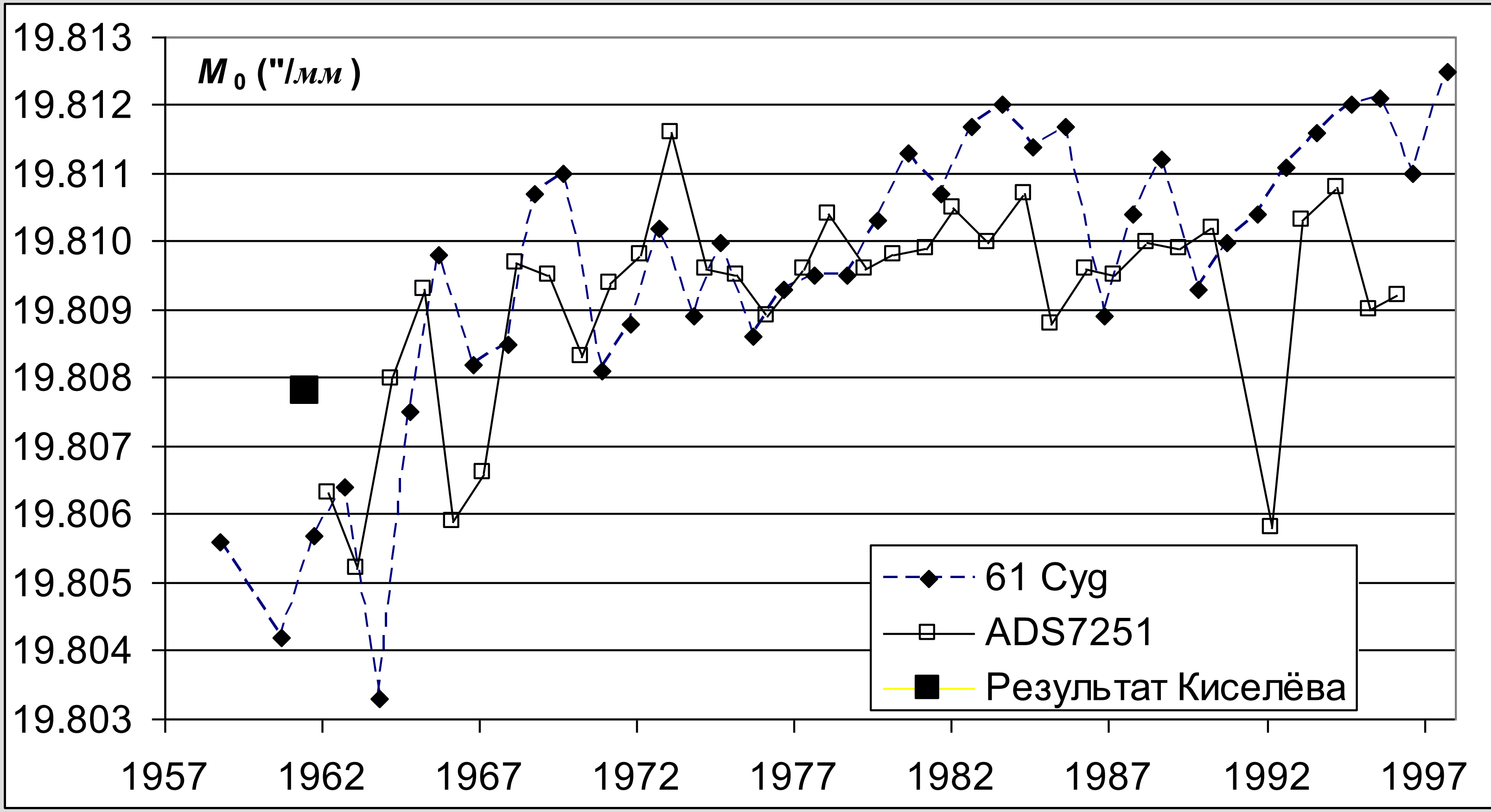
$$\Delta\sigma_1 = \sqrt{225\left(\Delta\alpha^{(s)} \cos\bar{\delta}\right)^2 + \left(\Delta\delta^{('')}\right)^2}$$

$$\Delta s = \sqrt{\Delta x^2 + \Delta y^2}$$

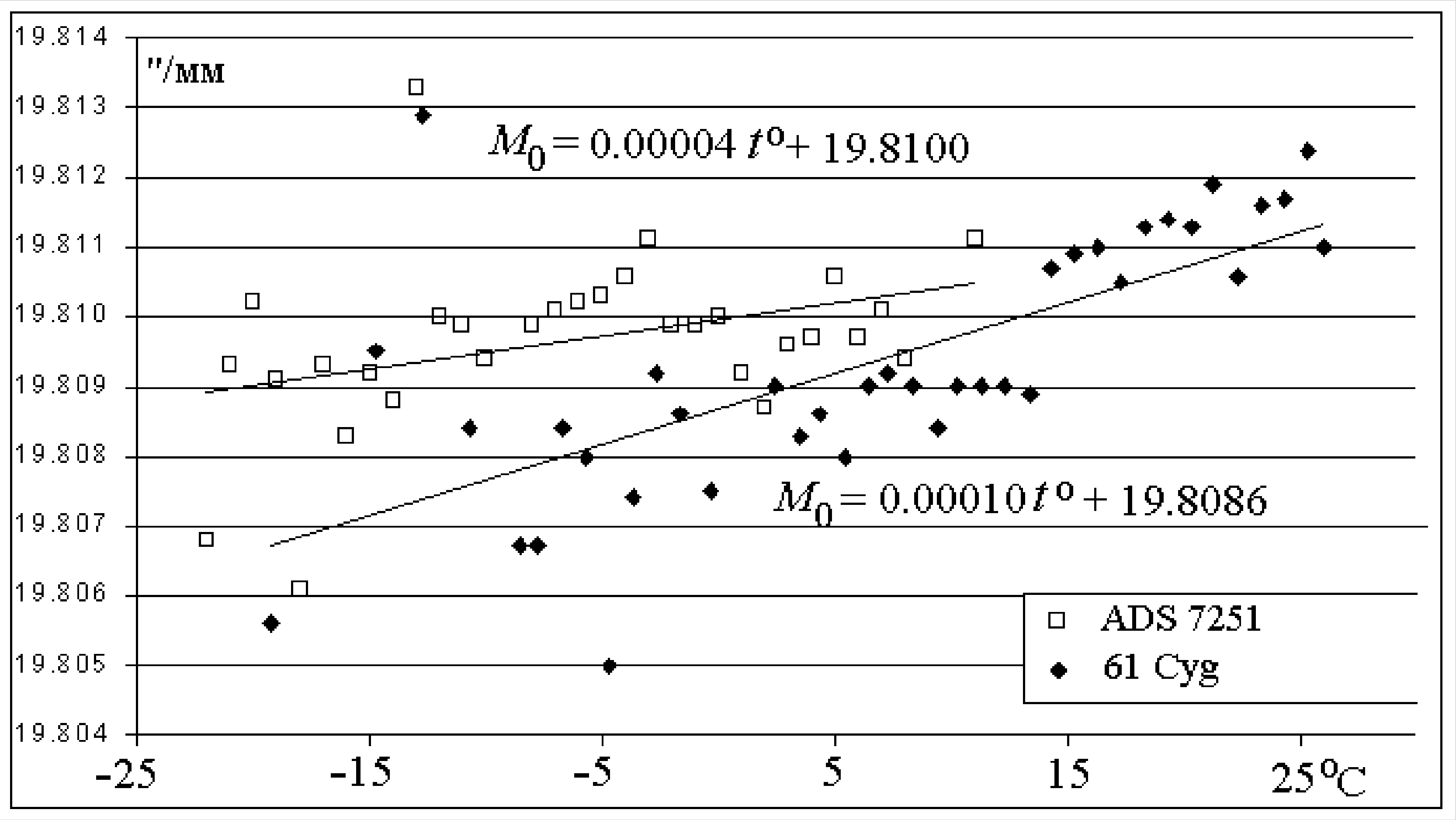
$$M_0 = M_* \left\{ 1 + r'^2 + \frac{\Delta s'^2}{12} - \frac{p'^2}{2} - \beta \left[1 + \left(\frac{\Delta x}{\Delta s} k_1 + \frac{\Delta y}{\Delta s} k_2 \right)^2 \right] \right\}$$



The change of geometrical scale.
The stars on the plates with 61 Cygni have been used.



The change of geometrical scale.
The stars on the plates with 61 Cygni and ADS 7251 have been used.



The change of M_0 with the temperature.

Conclusion

- We sumed up a history of measurements and processings of long-term numbers of observations at Pulkovo.

- Owing to automatic measurements we managed to process greater data files, and to test process of measurements, counting accuracy of measurements by means of the formulas accepted in astrometry.

- On automatic measurements for two stars 61 Cygni and ADS 7251 for the first time the mass-ratio is received, also the change of geometrical scale is revealed for the refractor.
- .
- Automatic measurements have confirmed those periodic fluctuations in movements of stars which have been found out at visual measurements earlier.
- Our stars are very interesting objects, and old plates can contain very interesting information which we have not else exhausted.
- We wish to all colleagues of success and overcoming of difficulties in development and in the mastering of new technics.