THE PRECISION OF MODERN THEORIES OF GALILEAN SATELLITES AS DERIVED BY THEIR COMPARISON WITH PHOTOGRAPHIC OBSERVATIONS MADE WITH THE 26" REFRACTOR AT PULKOVO OBSERVATORY

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ABSTRACT. The regular photographic observations of Galilean satellites has been made with 26" refractor at Pulkovo since 1975. The relative positions of satellites are obtained by means of "scaletrail" technique. During 1975 - 1979 over 600 observations of Galilean satellites were carried out. The observed positions were compared with the ephemeris based on Sampson's and Lieske's E-1 theories, the corresponding computations being made at the Institute for Theoretical Astronomy. The standard deviations of one observed relative position "Satellite minus Jupiter" don't exceed ±0ʺ.10. The comparison of Sampson's theory with observations showed some systematic error which can be considered as an error in longitude of about 1 min. Lieske's theory E-1 showed a better agreement with the observations, the absolute deviations not exceeding 0ʺ.3.

A construction of highly precision theories of motion of planet's satellites and of Galilean satellites, in particular, demands appropriately accurate observations (the error not exceeding 0ʺ.10). At present such observations of satellites can be obtained with the help of long-foci telescopes (focal length of about 10 m), using rigorous technique of astrometric reduction.

1. Observations

The photographic observations of Galilean satellites have been regularly carried out at Pulkovo since 1975 using the 26-inch refractor with the final goal to obtain precise differential satellite positions (relative to Jupiter). During 1975-1982, 220 photographic plates were taken with about 2000 exposures.

This paper presents the experience of determinations of Jovicentric coordinates of satellites from the 1975 - 1979 observations (64 plates, 600 observations, 58 nights). ORWO WO-3 plates were used in the observations. About 1-2 plates with 10 exposures were taken nightly, the exposure time being 30-60 sec.

The observing technique was as follows : at the begining of observations two exposures of Jupiter and satellites were made on the same

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daily parallel (east trail), then 10 exposures were performed. The observations were finished by a west trail. The measurements were made with the help of the measuring machine Ascorecord. The center of Jupiter's images was determined over four points at the ends of the polar and equatorial diameters of the planet.

2. Astronomical reduction

The astrometrical reduction was carried out on the basis of the method developed by A.A. Kisselev at Pulkovo for observations of double stars with long focus telescopes (Kisselev, 1971). This method does not require reference stars for the determinations of parameters of orientation, scale and refraction. The plate orientation was determined by means of the "trail-scale" technique, the scale was determined separately using special studies (Kisselev, 1964, 1973).

The effect of the variations of the orientation angle due to the motion of the system "satellites-Jupiter" was taken into account. The requirements on the orientation are very high when we reduce the satellite' observations because of large distance between them. In order to attain the results with an accuracy of $0''.10$, we should know the orientation angle to an accuracy of about 20" ($0^{\circ}.003$) with a maximum distance between the satellites of the order of 1000". Then the systematic error due to the inaccuracy of orientation will not exceed $0''.05$.

A comparison of results of independent reduction by two trails showed that the corresponding systematic error in differential coordinates of satellites did not exceed the calculated one ($0''.05$).

3. The results of reduction. Corrections of the phase of Jupiter

The Jovicentric coordinates of satellites $X = \Delta\alpha \cos\delta$, $Y = \Delta\delta$ were determined for every exposure on the plate ; then the average differences were obtained. The differences "satellite - satellite" were also calculated.

The corrections for Jupiter's phase were determined using simultaneous observations of two satellites in opposite elongations and a comparison of the observations with theory (Kisseleva, 1985). It was supposed that the error of the longitude of satellites in elongations was negligible. The phase corrections, derived in this manner exceeded those derived by the geometrical law by a factor of 3.6. These corrections were taken into account in the observations.

4. The ephemeris of Galilean satellites of Jupiter

For a comparison of the observations with modern theories of Sampson and Lieske the ephemeris calculated at the Institute for Theoretical Astronomy of the USSR Academy of Sciency was used.

Sampson's tables and Andoyer's method were used for the calculation of ephemeris by Sampson's theory (Sampson, 1910 ; Andoyer, 1915).

For the computation of ephemeris by Lieske's theory the constants and the expansions received by the Institute for Theoretical Astronomy from Lieske in table were used. The constants of this theory are similar to those in theory E-1 (Lieske, 1977, 1978).

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5. A comparison of the observations with the theories of Sampson and Lieske

By the agreement of O-C during one night the standard errors of one observation were found (Table 1).

Table 1. The standard errors of one observation.

Differences of coordinates	Standard errors of one image		Number of obs.	Standard errors of one plate		Number of plates
Satellite - - Jupiter	±0".101	±0".096	600	±0".039	±0".037	64
Satellite - Satellite	±0".060	±0".050	600	±0".020	±0".020	64

The O-C differences by Sampson's theory were given as linear dependences of the errors of phase, scale, orientation and longitude of satellites (as the zero point in Sampson's tables) :

$$(O-C)_x = KB(\phi)\ \sin Q + \tau\dot{X} + (\Delta M/M)X - \Delta\omega\ Y$$
$$(O-C)_y = KB(\phi)\ \cos Q + \tau\dot{Y} + (\Delta M/M)Y + \Delta\omega\ X \qquad (1)$$

Here X, Y are Jovicentric coordinates of satellites without the phase, K - is an unknown coefficient of phase, $B(\phi)$ - is a known phase function, calculated by the geometrical law, Q - is the positional angle of the point of the least brightness on the terminator of Jupiter, τ - is the unknown correction of longitude, $\Delta M/M$ - is the scale correction of the 26-inch refractor, $\Delta\omega$ - is the orientation correction.

This system (1) was solved by the least squares method for X and Y jointly for each of the four satellites ; thus the following unknown quantities were found (Table 2) :

Table 2. The solution of system 1

K	$\Delta M/M$	$\Delta\omega$	τ_1	τ_2	τ_3	τ_4	τ(min)
-3.65	-0.00023	-0.00010	+1.05	+0.74	+0.39	+1.27	+0.86
±0.31	± 13	± 10	± 15	± 18	± 33	± 41	± 27

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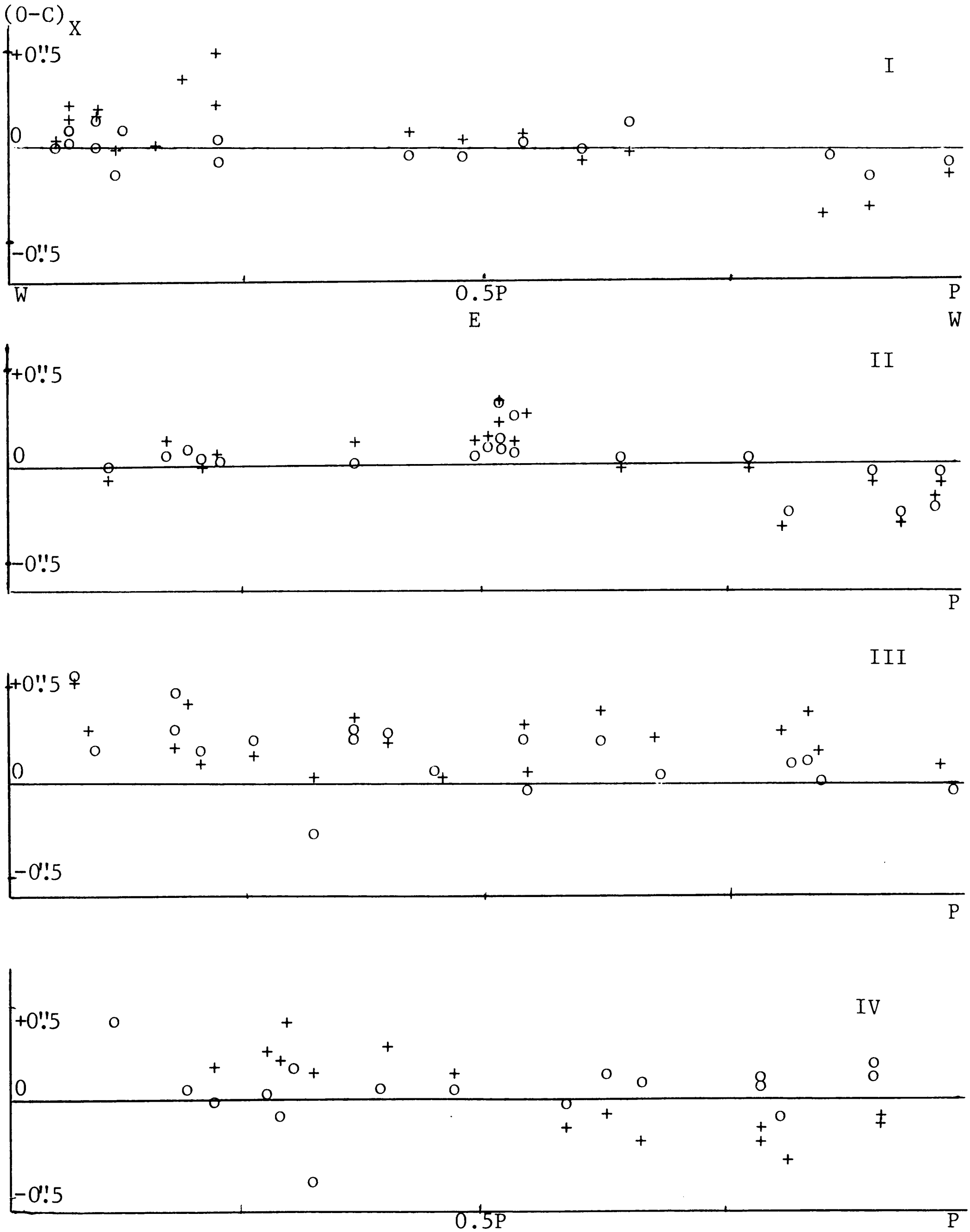

Figure 1. The comparison of observations St/J with the ephemeris

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Hence, Sampson's theory has an error of longitude (or the error of the zero point of the time scale) of the order of 1 min. The procedure for the analysis of observations and their comparison with the ephemeris was carried out using Lieske's theory with the exception of the solution of system (1).

Figure 1 presents a comparison of the observations with the theories of Sampson and Lieske for the period 1975-1977. The observations are grouped into mean places during the night (10 - 20 observations). The $(O-C)_x$ are given as functions of satellite positions on the Jovicentric orbit.

The analysis of $(O-C)_x$ by Sampson's theory in Figure 1 confirms the existence of systematic error in longitude, especially for the 1^{st} and 4^{th} satellites. (O-C) calculated by the theory of Lieske doesn't comprise this error. As a rule the quantities (O-C) don't exceed 0$''$.3. They are twice smaller for the Lieske's theory then for Sampson's theory. There are residual errors for the 3^{d} satellite.

By the curves of (O-C) standard deviations of one observation for the each satellite during one night were calculated. They are given in table 3.

Table 3 Standard deviations of one observation for the period 1975-1977 (about 300 obs)

Theory	I	II	III	IV	Number of meam places
Sampson	±0$''$.111	±0$''$.122	±0$''$.123	±0$''$.110	28
Lieske	±0$''$.080	±0$''$.066	±0$''$.103	±0$''$.122	28

The quantities of the second line in table 3 suggests a better precision of Lieske's theory.

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DISCUSSION

Lieske : I would like to say that the observations of Galilean satellites in Pulkovo are the most precise and they fit with the theory better then all other observations.

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