# CCD-OBSERVATIONS OF GALILEAN SATELLITES OF JUPITER DURING THEIR MUTUAL OCCULTATIONS AND ECLIPSES IN 2003 AT PULKOVO OBSERVATORY

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ABSTRACT. CCD-observations of mutual events in the system of Galilean satellites of Jupiter were made with Pulkovo 26-inch Refractor. The results of astrometric and photometric CCD-observations have been obtained for 19 and 20 events correspondingly. The internal accuracy of the moments of maximal phase of the events is $0.5\,sec \div 4.8\,sec$ for photometric observations and $0.7\,sec \div 7\,sec$ for astrometric observations. The agreement between the moments of maximal phase of the events determined from astrometric and photometric observations is within $10\,sec$. The minimal distances between satellites obtained from astrometric observations of occultations are $0.05'' \div 1''$ with accuracy $0.01'' \div 0.02''$. The differences between observational and ephemerides moments of the maximal phase of the events are within $2\,sec \div 24\,sec$.

## 1. INTRODUCTION

The CCD-observations of mutual events (occultations and eclipses) in the system of Galilean Satellites of Jupiter were made during the period from January till April 2003 at Pulkovo observatory with 26-inch Refractor and CCD ST-6. The description of the parameters of CCD ST-6 and the methods and programs of observations were presented in paper Izmailov I.S. et. al. 1998. The observations were made accordance to the ephemerides of mutual events calculated by N.V.Emelianov. The experience of such observations have been collected in 1997 during previous campaign of accumulated observations of mutual events (N.V. Emelianov et al. 2000).

The 20 photometric observations of 10 occultations and 10 eclipses have been done. Photometric observations were accompanied by astrometric observations (19 events). From 100 to 1000 CCD-frames were used for each photometric observations of occultations and eclipses. The moments of time were determined in the time scale UTC with accuracy $0.05\,sec$. The time delay between neighboring CCD-frames is less than 10 sec. The time of exposures for each frame was about of $0.1sec$. The combination of yellow and blue filters with effective wave length $550\,nm$ was used for observations.

## 2. THE RESULTS OF PHOTOMETRIC OBSERVATIONS

The light curves present changing with time of sums or differences of magnitudes of satellites during occultations or eclipses. It have been represented using Gaussian model:

$$m(t) = \exp\left(-a(t - T_0)^2 - b\right) + c.$$

Parameter $a$ characterizes the duration of the event, parameter $b$ shows the maximal decreasing of brightness and $c$ is a free parameter.

The parameters of the model were determined using gradient algorithm of the nonlinear least-squares method.

Table 1 and Figures 1, 2 present the results of 11 most successful observations. The others 8 of ones require further investigations.

Table 1: The results of photometric CCD-observations of the mutual events of Jupiter's Galilean satellites.

| date/event | $T_0 \pm \sigma_{T_0}$ | $T_1$ | $T_2$ | $\Delta m_{max} \pm \sigma_m$ |
|---|---|---|---|---|
| | $h\ m\ s$ | $h\ m\ s$ | | |
| 0106 2E1 | 23 32 50.879 ± 00.657 | 23 25 30.815 | 23 40 10.942 | 0.676 ± 0.022 |
| 0110 2O1 | 19 26 24.578 ± 04.966 | 19 17 20.195 | 19 35 28.961 | 0.254 ± 0.045 |
| 0203 4O1 | 17 12 12.794 ± 00.676 | 17 09 27.472 | 17 14 58.116 | 0.597 ± 0.023 |
| 0203 2O3 | 23 31 18.518 ± 00.977 | 23 24 18.508 | 23 38 18.529 | 0.285 ± 0.006 |
| 0203 2E3 | 23 39 43.847 ± 01.096 | 23 32 12.275 | 23 47 15.419 | 0.254 ± 0.005 |
| 0218 4E3[1] | 20 48 37.401 ± 02.155 | 20 41 35.689 | 20 55 39.113 | 0.567 ± 0.028 |
| 0306 1O2[2] | 19 47 41.088 ± 02.100 | 19 46 21.140 | 19 49 01.036 | 0.331 ± 0.055 |
| 0315 3E4 | 22 14 43.936 ± 00.787 | 22 07 05.318 | 22 22 22.554 | 0.994 ± 0.016 |
| 0320 1O2 | 23 52 21.334 ± 00.946 | 23 50 59.892 | 23 53 42.776 | 0.163 ± 0.018 |
| 0326 2E1[3] | 20 40 44.675 ± 04.810 | 20 39 32.469 | 20 41 56.880 | 0.215 ± 0.048 |
| 0421 1O2 | 21 29 04.764 ± 00.725 | 21 27 37.407 | 21 30 32.121 | 0.210 ± 0.021 |

The first two symbols in date field denote month and the last two symbols denote day. The occultations are denoted by "O" symbol and eclipses are denoted by "E" symbol. The names of satellites are denoted by digits: 1 – Io, 2 – Europe, 3 – Ganymede, 4 – Callisto.

$T_0$ – moment of the maximal phase of the event (UTC),
$T_1$ and $T_1$ – moments of beginning and ending of the event,
$\Delta m_{max}$ – maximal decreasing of brightness,
$\sigma_{T_0}$ and $\sigma_m$ – errors of $T_0$ and $\Delta m_{max}$.

Remarks for few results in Table 1:
1 – observations have been made through holes between clouds,
2 – the transparent clouds was covering the sky during observations,
3 – strong wind during observations.

The values $\sigma_m$ and $\sigma_{T_0}$ were estimated in accordance to:

$$\sigma_m = \sqrt{\frac{\sum_{i=1}^{n} (mag_i - m(t_i))^2}{n-4}}, \quad \sigma_{T_0} = \sigma_m \cdot \left( \sum_{i=1}^{n} \left( \frac{\partial m(t)}{\partial T_0}\Big|_{t=t_i} \right)^2 \right)^{-1/2}.$$

Here $n$ is number of separate measurements of the satellites magnitudes and $mag_i$ is the sum or the difference of satellites magnitudes at the moment $t_i$.

The value $\Delta m_{max}$ was calculated using expression:

$$\Delta m_{max} = |m(T_0) - c| .$$

The assumption $m(T_{1,2}) = c + \sigma_m$ was used for calculation of the moments of beginning and ending of the events ($T_1$ and $T_2$).

## 3. THE RESULTS OF ASTROMETRIC OBSERVATIONS

The astrometric observations were started before the events and finished after the events. The whole period of observations of one event was 1 - 1.5 hours. The moments of minimal distances, the minimal distances and relative velocities of satellites for the occultations with their errors were determined. The errors of minimal distances are within $0.01'' \div 0.02''$, the errors of determination of the moments of minimal distances are within $0.7\,sec \div 7\,sec$. The minimal distances are within $0.05'' \div 1''$ (Kiseleva T.P. et. al. 2002).

The results of astrometric observations of occultations are presented in Table 2 (the lines without date and the denotations of the events contain the RMS errors of all values listed in previous line). $T_0$ is the moment of minimal distances; $r_0$ is the minimal distances; $X, Y$ - are the components of $r_0$ in RA and DECL; $V_x, V_y$ are the components of relative velocities of satellites; $N$ is the number of CCD-frames in series.

It would be desirable to emphasize, astrometric observations of occultations allow to determine the parameters of occultations (moments of the maximal phase, minimal distances) also in the case when the photometric observations were not made successfully (for example, the observations at 7.01, 17.01, 15.02, 25.03, 01.04 in Table 2).

Table 2: The results of astrometric CCD-observations of mutual occultations.

| Data and Events | $T_0$ h m s | $N$ | $r_0$ arcsec | $X$ arcsec | $Y$ arcsec | $V_x$ arcsec/h | $V_y$ arcsec/h |
|---|---|---|---|---|---|---|---|
| 01 07 2O1 | 01 25 15.858 | 197 | 1.0270 | 0.3419 | 0.9684 | -4.9956 | 1.7634 |
| | ±7.285 | | ±0.0083 | ±0.0107 | ±0.0080 | ±0.0155 | ±0.0115 |
| 01 16 4O2 | 00 43 58.148 | 300 | 0.4907 | -0.1546 | -0.4657 | -12.5194 | 4.1570 |
| | ±2.887 | | ±0.0094 | ±0.0107 | ±0.0092 | ±0.0025 | ±0.0022 |
| 02 03 4O1 | 17 12 02.918 | 149 | 0.0479 | -0.0152 | -0.0454 | -27.3507 | 9.1727 |
| | ±0.972 | | ±0.0072 | ±0.0079 | ±0.0072 | ±0.0230 | ±0.0210 |
| 02 03 2O3 | 23 30 49.057 | 110 | 0.3334 | 0.1058 | 0.3162 | -11.6509 | 3.8977 |
| | ±1.238 | | ±0.0023 | ±0.0044 | ±0.0020 | ±0.0032 | ±0.0014 |
| 02 15 2O1 | 19 15 56.453 | 238 | 1.0943 | -0.3243 | -1.0451 | -16.4691 | 5.1112 |
| | ±0.875 | | ±0.0044 | ±0.0041 | ±0.0044 | ±0.0109 | ±0.0116 |
| 03 06 1O2 | 19 47 42.557 | 136 | 0.3506 | 0.1040 | 0.3348 | 31.7936 | -9.8765 |
| | ±0.835 | | ±0.0115 | ±0.0072 | ±0.0118 | ±0.0188 | ±0.0310 |
| 03 20 1O2 | 23 52 15.444 | 103 | 0.4524 | 0.1333 | 0.4323 | 30.2036 | -9.3120 |
| | ±0.858 | | ±0.0076 | ±0.0075 | ±0.0076 | ±0.0225 | ±0.0228 |
| 03 25 2O3 | 20 47 57.791 | 157 | 0.7415 | -0.2022 | -0.7133 | -16.0298 | 4.5449 |
| | ±1.148 | | ±0.0102 | ±0.0044 | ±0.0105 | ±0.0143 | ±0.0343 |
| 04 01 2O3 | 23 55 34.990 | 62 | 0.9353 | -0.2591 | -0.8987 | -16.3076 | 4.7015 |
| | ±4.250 | | ±0.0216 | ±0.0199 | ±0.0217 | ±0.0210 | ±0.0230 |
| 04 21 1O2 | 21 29 05.551 | 246 | 0.3621 | 0.1062 | 0.3462 | 25.5804 | -7.8438 |
| | ±0.785 | | ±0.0048 | ±0.0059 | ±0.0047 | ±0.0214 | ±0.0171 |

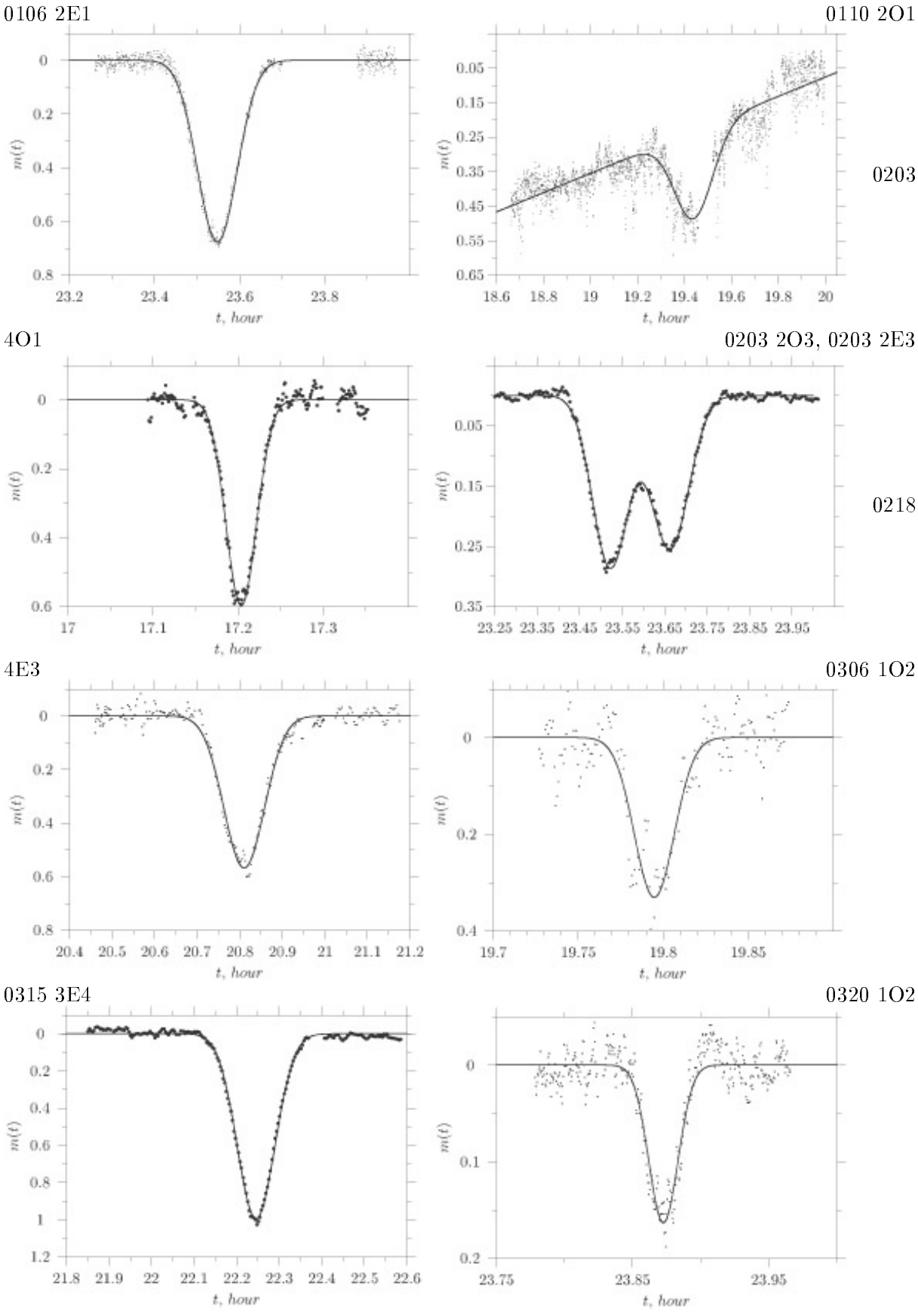


Figure 1: The light curves that have been derived from the results of photometric CCD-observations.

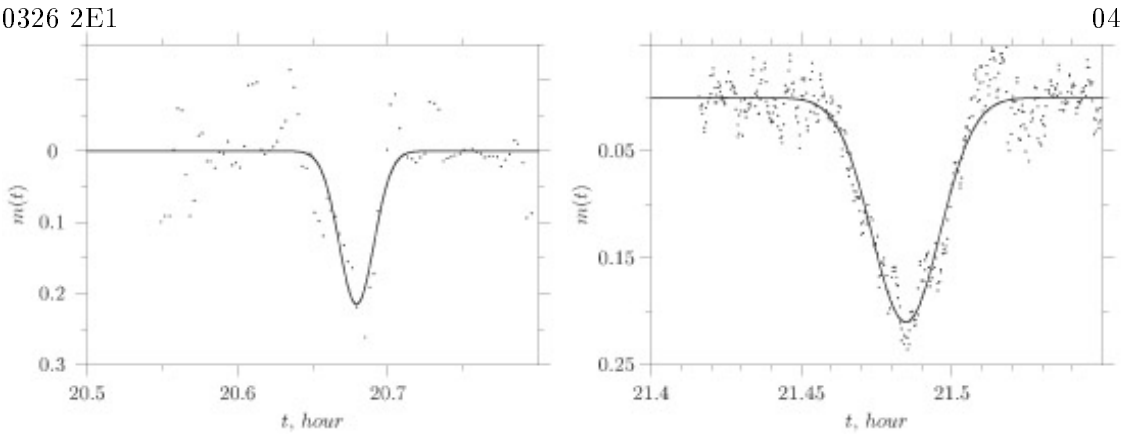


Figure 2: The light curves that have been derived from the results of photometric CCD-observations.

## 5. CONCLUSIONS

The agreement between results of astrometric and photometric determination of the moments of the maximal phase of occultations is in the limits of 10 *sec*. The comparison of moments of events derived from photometric observations with the ephemerides are presented in Table 3.

Table 3: The comparison of the moments of mutual events with the ephemerides.

| Data | Events | (O - C)$T_0$ s |
|---|---|---|
| 01 06 | 2E1 | -7.121 |
| 02 03 | 4O1 | +23.794 |
| 02 03 | 2O3 | +14.146 |
| 02 03 | 2E3 | -0.792 |
| 02 18 | 4E3 | -1.600 |
| 03 06 | 1O2 | -6.912 |
| 03 15 | 3E4 | +13.436 |
| 03 20 | 1O2 | -7.166 |
| 03 26 | 2E1 | -7.325 |
| 04 21 | 1O2 | -12.236 |

The Table 3 demonstrates that the accuracy of moments of events is equal to $\pm 12.0 sec$. This value corresponds to relative angular distances between two satellites less than $0.107''$. It testifies about small errors of observations and ephemerides.

The astrometric and photometric observations of mutual events in the system of Galilean satellites may be used for the improvement of the theories of motions of satellites, for the construction of the model of events and to the more accurate definition of sizes and figures of satellites.

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## 6. REFERENCES

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