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THE ANALYSIS OF MUTUAL PHENOMENA OF THE GALILEAN SATELLITES OF JUPITER IN 1985

Arata Sengoku, Kouji Terai[1], Kunio Kenmotsu, Seiji Fuchinoue, Takeharu Miyake[2], Eiki Nishimura
Kunio Matsumoto, Masayuki Sawa, Hiroshi Sasaki[3], Takeo Uchiyama, Katsuhiko Murakami,
Sinichi Kanagawa[4]

In 1985, mutual phenomena of the Galilean satellites of Jupiter took place. At the hydrographic observatories (Bisei, Simosato and Sirahama) 14 mutual phenomena (23 light curves) were observed. From 11 light curves of good quality, the longitude corrections of three inner satellites for E-2 (Lieske, 1980) are estimated to be $\Delta 1_1$=4.2 ±1.6 (x 10^{-4}), $\Delta 1_2$=-1.0 ±0.4 (x 10^{-4}) and $\Delta 1_3$=0.0 ±1.0 (x 10^{-4}). This results are mostly in accordance with those by Aksnes & Franklin (1976).

key words the Galilean satellites – mutual phenomena

1. Introduction

The motions of Galilean satellites of Jupiter are very much complicated. Each Galilean satellite is perturbed by the oblateness of Jupiter, the gravitational force of the Sun and the deep resonance effect among three inner satellites. This variety of disturbing forces have fascinated celestial mechanicians. Furthermore, the Galilean satellites revolve around Jupiter very rapidly, and the degradation of the ephemerides is inevitable.

At present, there are two precise ephemerides, E-2 (Lieske, 1980) and G-5 (Arlot, 1982), which are both based on the Lieske's theory (1977). Although the inner error of the Lieske's theory is estimated to be about 10km in linear scale and about 2 arc second in jovicentric angle, the discrepancy between above two ephemerides (E-2 and G-5) is rather large. It is because they used different data sets to determine the parameters in the Lieske's theory. The comparison among each of the two ephemerides and the observation is still necessary.

There are various methods to observe the position of the Galilean satellites. The observation of mutual phenomena is the most precise method at present.

The mutual phenomena of the Galilean satellites occur every half jovian year when the Earth or the Sun goes though the equatorial plane of Jupiter. In 1985 this condition was satisfied around the opposition of Jupiter with the Sun, and this good condition led to a large quantity and high quality of data.

2. Observations and Data processing

2.1 Observations

At the three hydrographic observatories (Table 1), thanks to the predictions by Arlot (1984), the

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[1] Satellite Geodesy Office

[2] Bisei Hydrographic Observatory, 6th. R. M. S. Hqs.

[3] Simosato Hydrographic Observatory, 5th. R. M. S. Hqs.

[4] Sirahama Hydrographic Observatory, 3rd. R. M. S. Hqs.

Table 1. The hydrographic observatories

Observatory	Bisei	Simosato	Sirahama
telescope aperture	60cm	60cm	30cm
f	940cm	1000cm	500cm
photomultiplier	EMI9502B	EMI9789B	EMI9502B
latitude	34°41′	33°34′	34°43′
longitude	133°34′	135°56′	138°59′

Table 2. The observed mutual phenomena

Date	Event	Time (TDT)		Magnitude	Distance	Observatory	Altitude	Voltage	Diaphram	k	Seeing
		h	m			*	°	V	″		
1985 6.17	3O1p	17	44	0.74	5.8	B	37	550	20	–	1/b
7.26	4O2t	12	35	1.21	7.4	B	26	720	20	0.033	2/a
8.13	3O2p	13	14	0.67	9.3	B	33	640	30	0.526	1/a
						Sm	35	630	20	–	1/a
						Sr	35	600	35	–	1/b
	3E2p	14	06	0.88	9.3	B	36	710	30	–	1/a
						Sm	38	610	15	–	1/a
						Sr	37	650	25	–	1/b
8.20	3O2p	16	23	0.64	9.3	B	26	650	30	0.006	2/a
	3E2p	17	58	0.44	9,4	B	14	730	30	0.222	1/a
8.24	1O3p	15	08	0.22	4.9	B	33	790	30	0.223	2/a
						Sr	32	595	35	0.333	–
9. 3	1E2p	10	54	0.32	6.3	B	28	780	30	–	1/b
						Sm	30	720	15	0.978	1/a
9.10	1E2p	13	59	0.45	6.7	B	33	730	30	–	2/a
						Sm	32	620	15	–	1/b
						Sr	30	680	25	–	3/c
10. 2	4E1a	19	37	0.12	5.4	Sm	32	610	15	–	2/b
10.12	1E2p	13	34	0.56	7.0	Sm	18	630	15	0.661	2/b
11.20	4O1p	09	29	0.25	5.9	B	33	720	20	–	1/a
11.25	2E1a	10	29	0.12	3.8	B	25	750	20	0.583	2/a
						Sm	24	620	15	0.026	1/a
12.15	1O2p	08	56	0.60	4.4	Sm	26	590	15	0.855	1/a

*B: Bisei, Sm: Simosato, Sr: Sirahama

mutual phenomena were observed photoelectrically.

We did not use any filter. The background level was measured once a few minutes by drifting diaphram toward the normal direction to Jupiter. The accuracy of time is higher than 0.1 sec, since it is calibrated by JJY.

Table 2 is the list of observed phenomena. The type of event is identified by the notation such as jOk and jEk for "satellite j occults satellite k" and "satellite j eclipses satellite k", respectively, and p, a and t mean partial, annular and total phenomena, respectively. Columns 4 and 5 give the magnitude and the distance to the center of Jupiter in jovian radius. Column 10 contains sky condition data, stability of star image and transparency. Stability of star image is expressed in three grade, 1, 2 and 3 meaning good, fair and poor, respectively. Transparency is also expressed in three grade, a, b and c which mean good, fair and poor, respectively.

2.2 Data processing

Data processing consists of three procedures, i.e., background noise correction, smoothing and atmospheric extinction.

First, the background noise correction is considered. We have subtracted the background noise which is estimated by linear interpolation.

Next, the data were smoothed by 5 points weighted mean formula which is expressed as follows.

$$y_i = \sum_{j=-2}^{2} w_j x_{i+j} \qquad \ldots\ldots(1)$$

$$w_{\pm 2} = -3/35$$
$$w_{\pm 1} = 12/35$$
$$w_0 = 17/35$$

where x_i is the raw intensity, y_i is the smoothed one and w_i is the weight.

The correction of atmospheric extinction is expressed as follows.

$$I = I_0 \exp(-k \sec z) \qquad \ldots\ldots(2)$$

where I_0 and I are the initial and final intensities, z is the zenith distance and k is the extinction coefficient.

We estimate the extinction coefficient so that the levels before and after the phenomenon are equal. In some cases, when we could not observe a whole phenomenon, we do not estimate the extinction coefficient. The extinction coefficient of each phenomenon is listed in table 3. The final light curves are shown in figure 1 to 17.

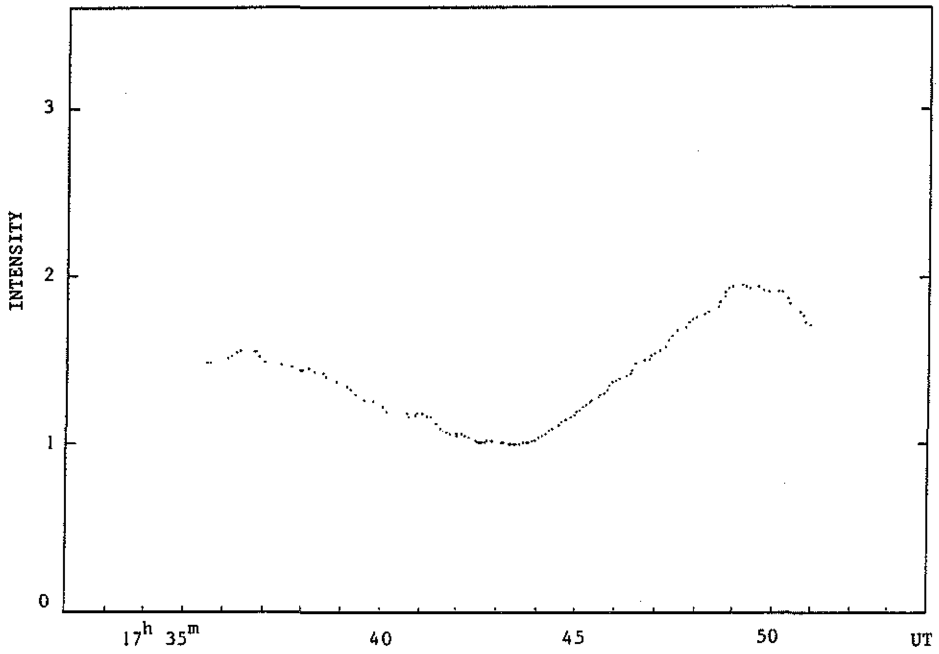

Figure 1. J3 occults J1 partially
on June 17, 1985 (Bisei)

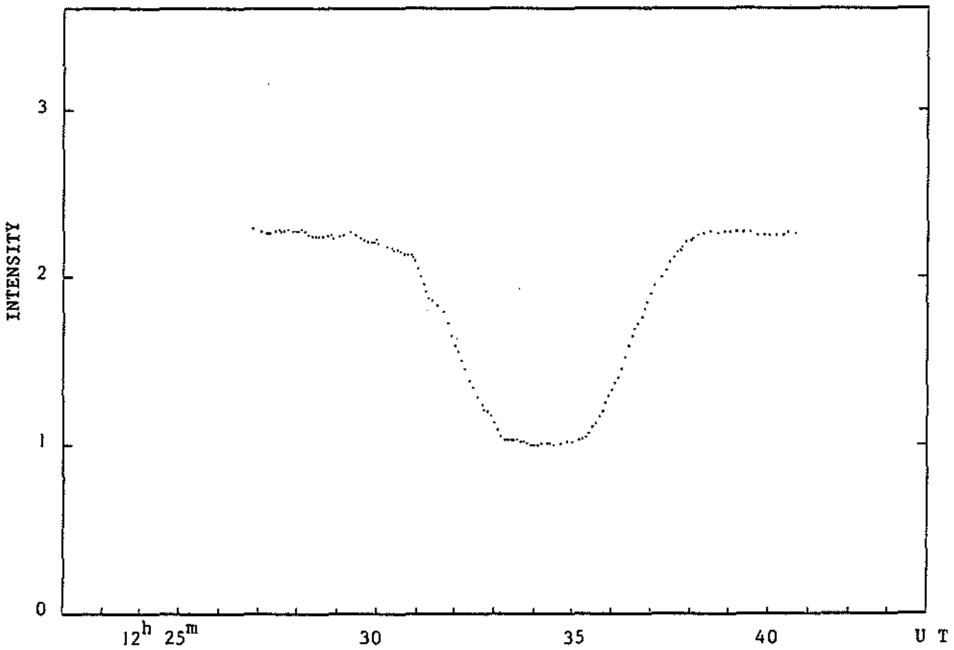

Figure 2. J4 occults J2 totally
on July 26, 1985 (Bisei)

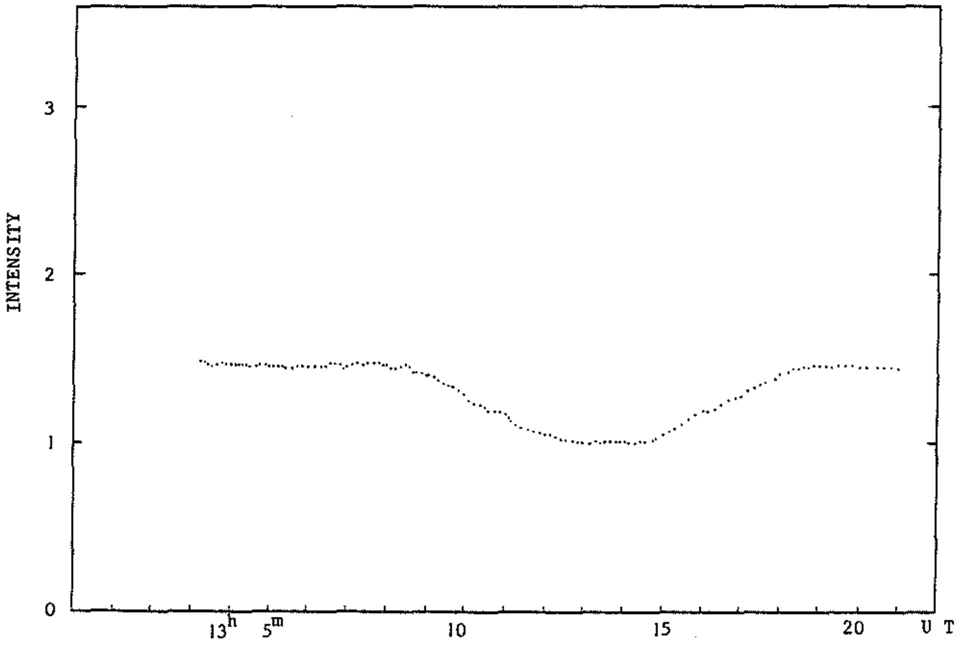

Figure 3. J3 occults J2 partially
on August 13, 1985 (Bisei)

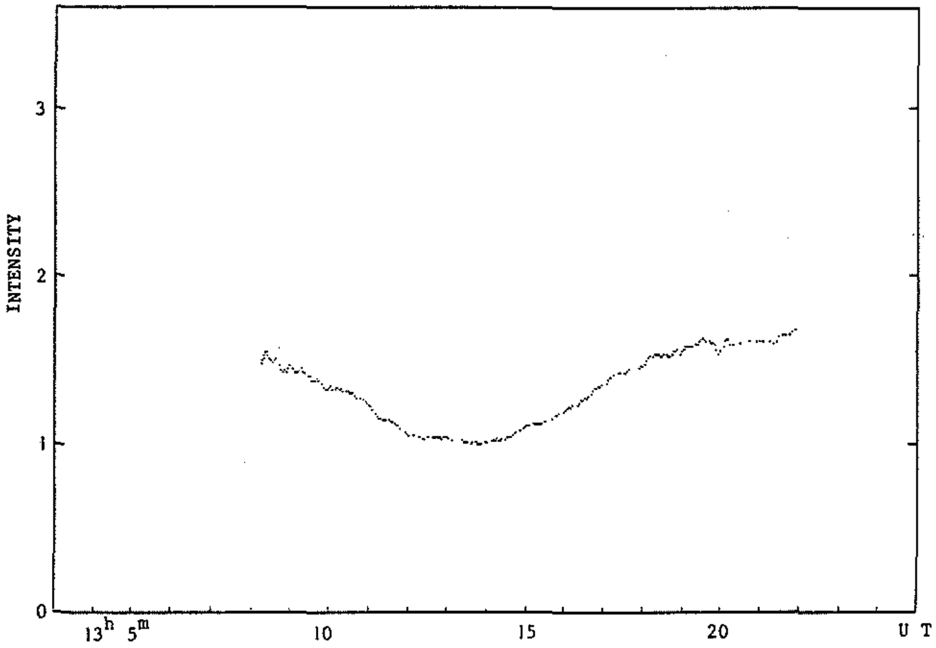

Figure 4. J3 occults J2 partially
on August 13, 1985 (Simosato)

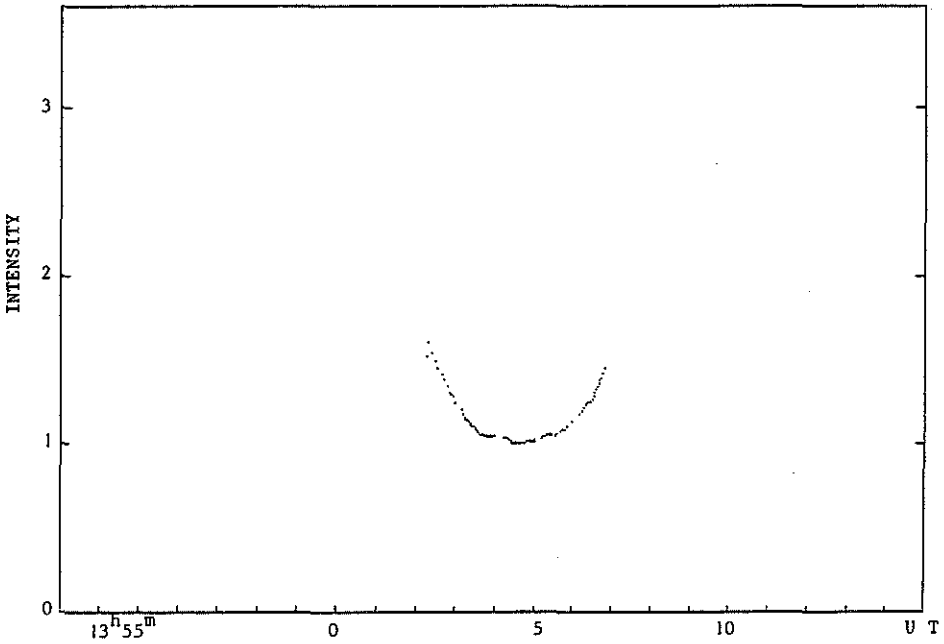

Figure 5. J3 eclipses J2 partially
on August 13, 1985 (Simosato)

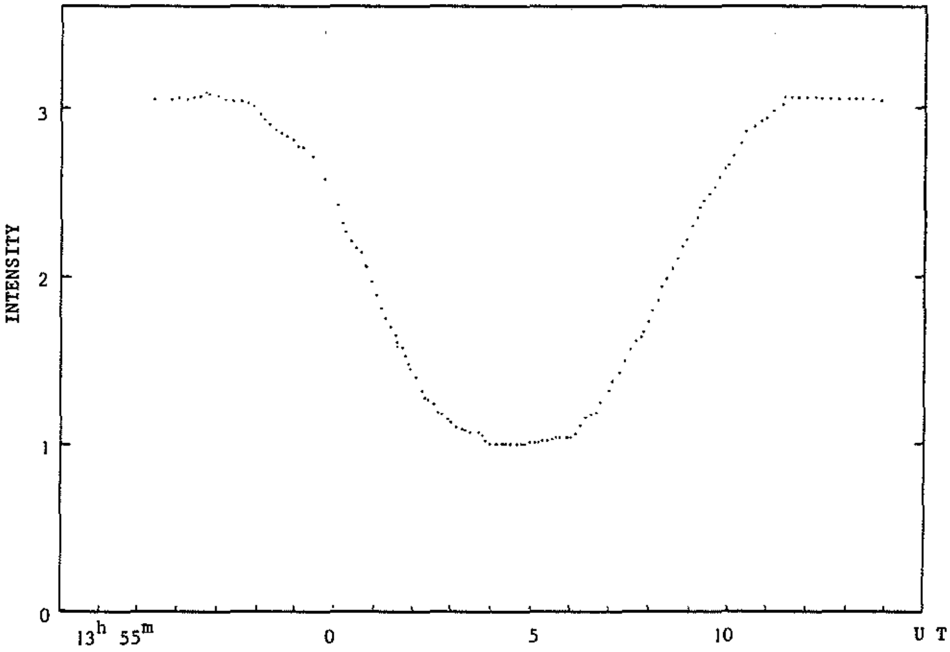

Figure 6. J3 eclipses J2 partially
on August 13, 1985 (Bisei)

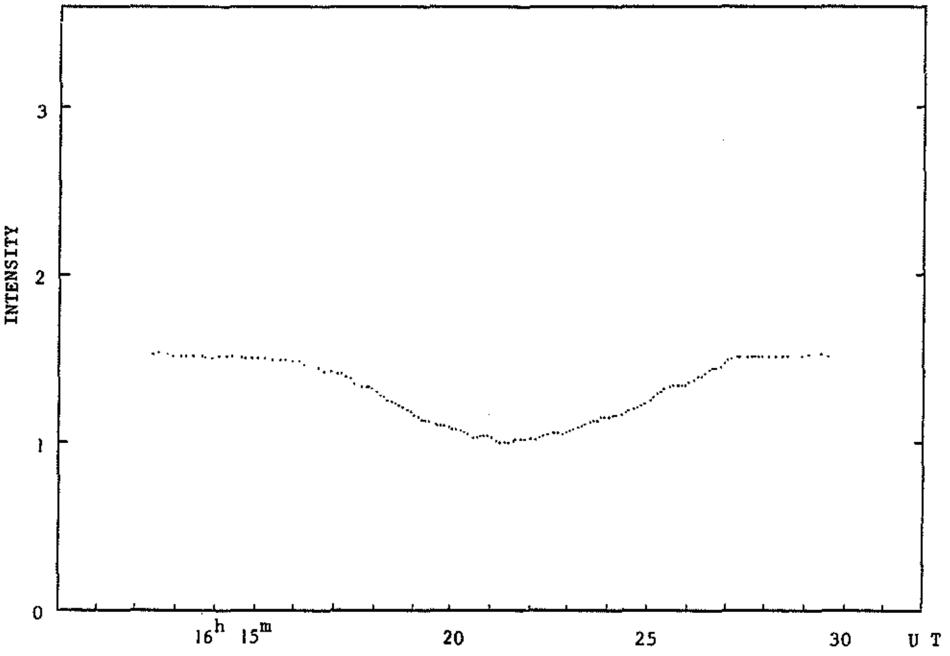

Figure 7. J3 occults J2 partially
on August 20, 1985 (Bisei)

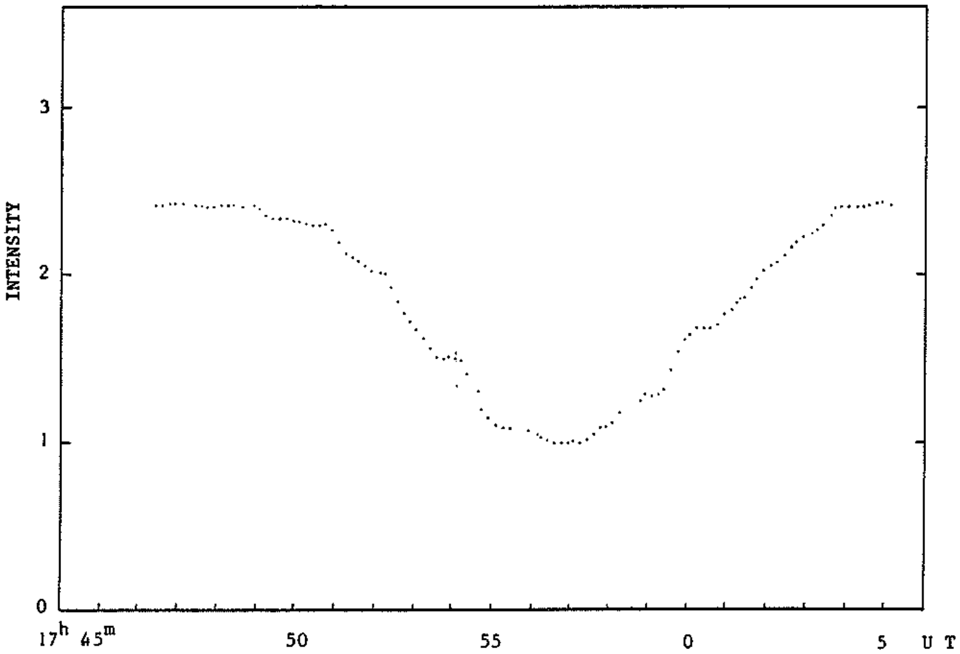

Figure 8. J3 eclipses J2 partially on August 20, 1985 (Bisei)

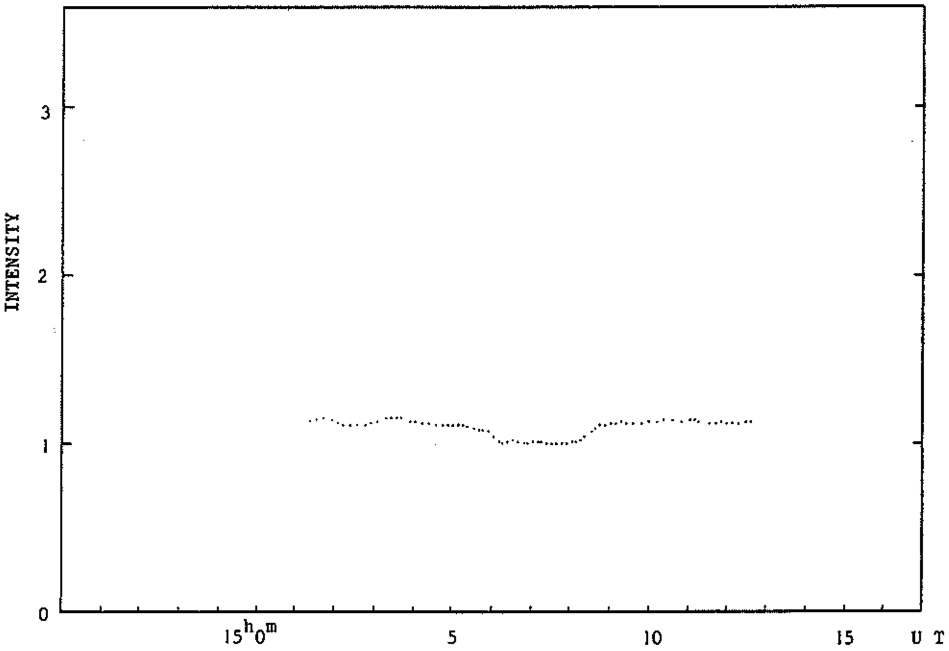

Figure 9. J1 occults J3 partially on August 24, 1985 (Bisei)

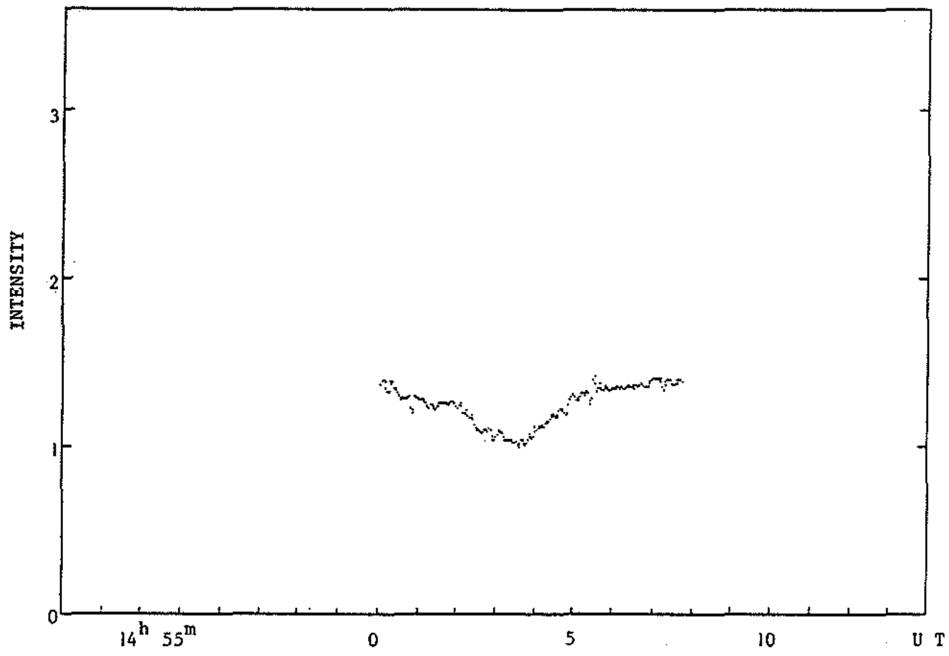

Figure 10. J1 occults J3 partially
on August 24, 1985 (Sirahama)

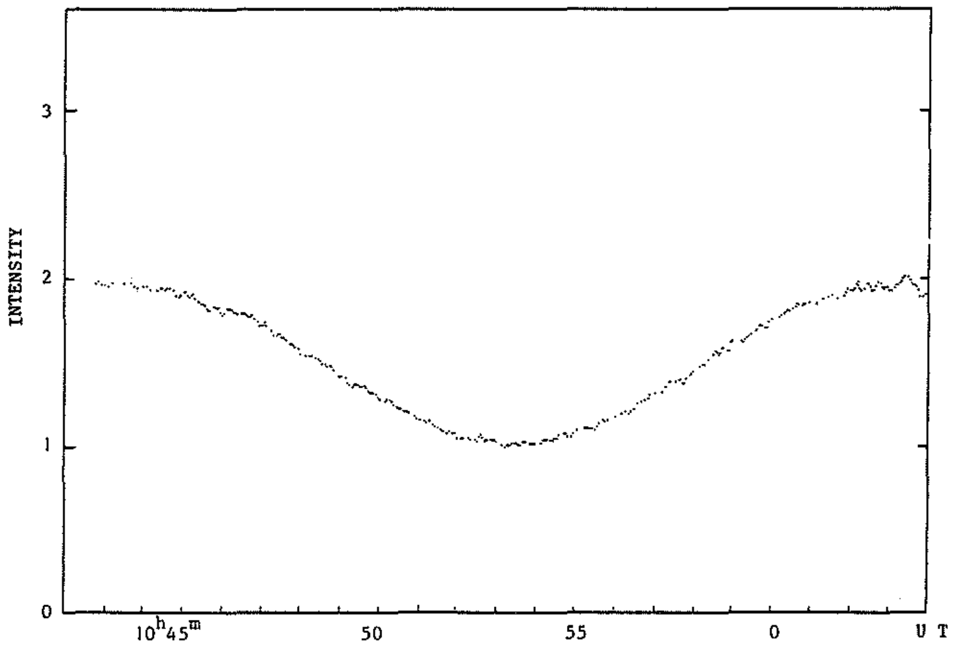

Figure 11. J1 eclipses J2 partially
on September 3, 1985 (Simosato)

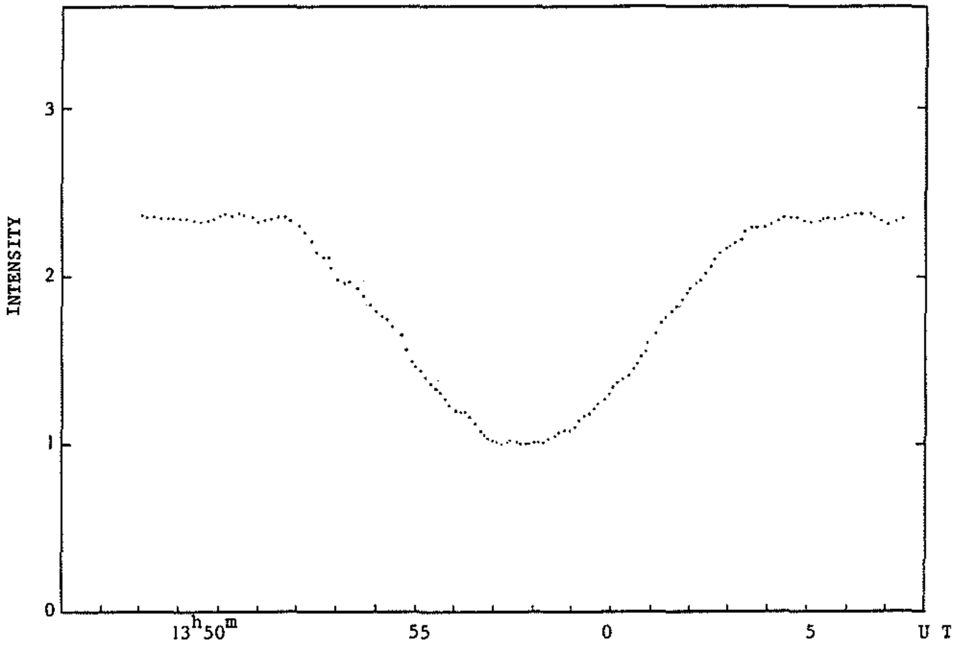

Figure 12. J1 eclipses J2 partially
on September 10, 1985 (Bisei)

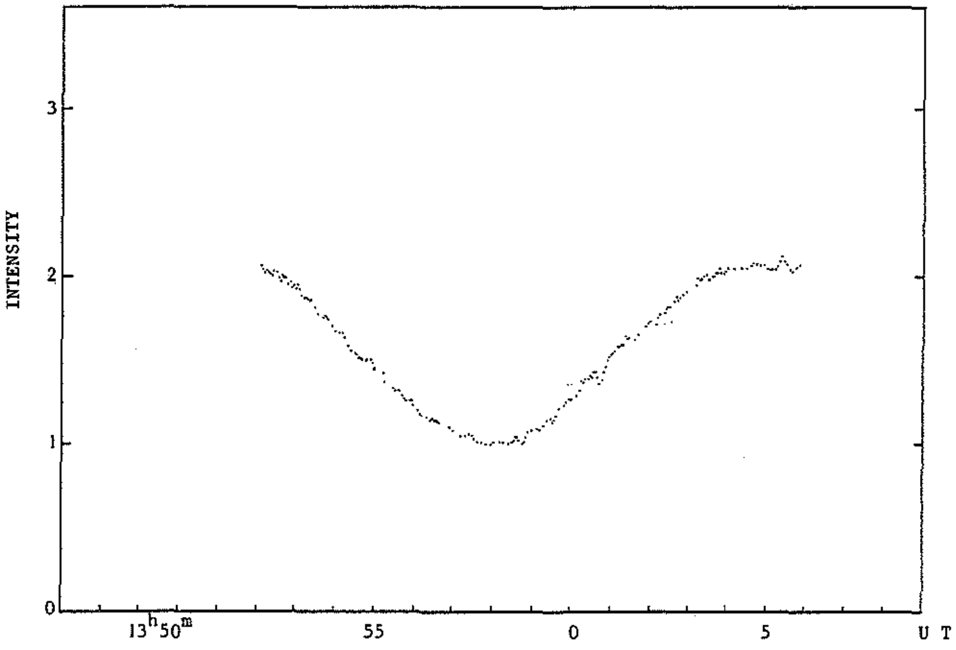

Figure 13. J1 eclipses J2 partially
on September 10, 1985 (Simosato)

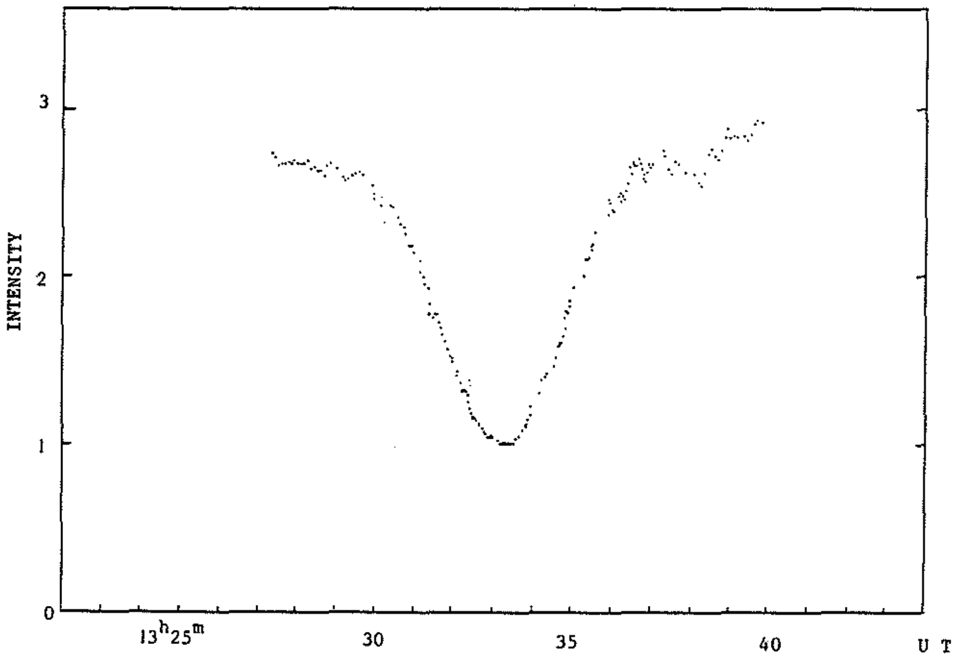

Figure 14. J1 eclipses J2 partially
on October 12, 1985 (Simosato)

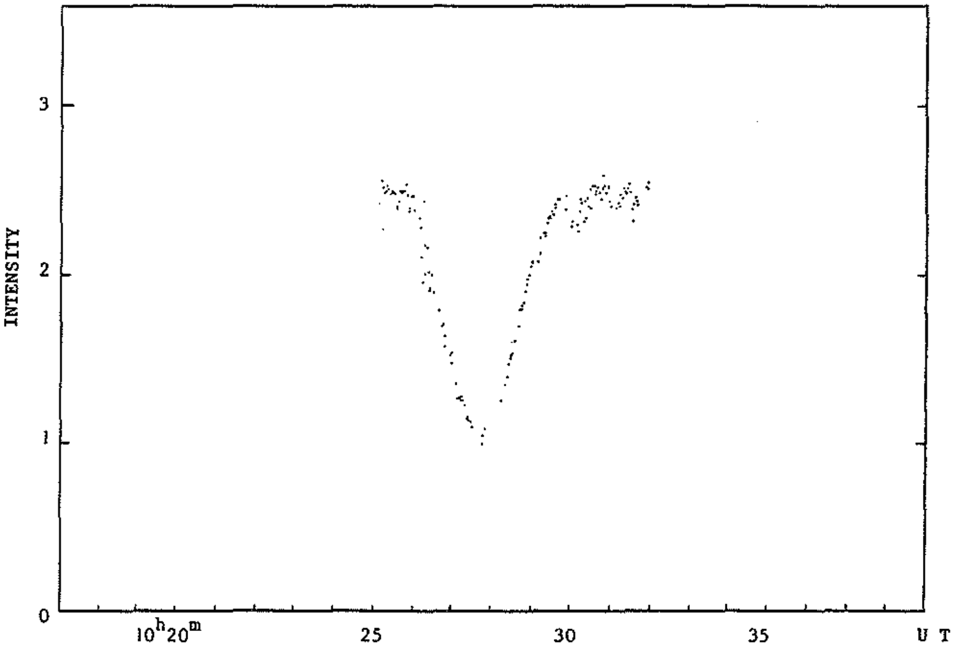

Figure 15. J2 eclipses J1 annularly
on November 25, 1985 (Simosato)

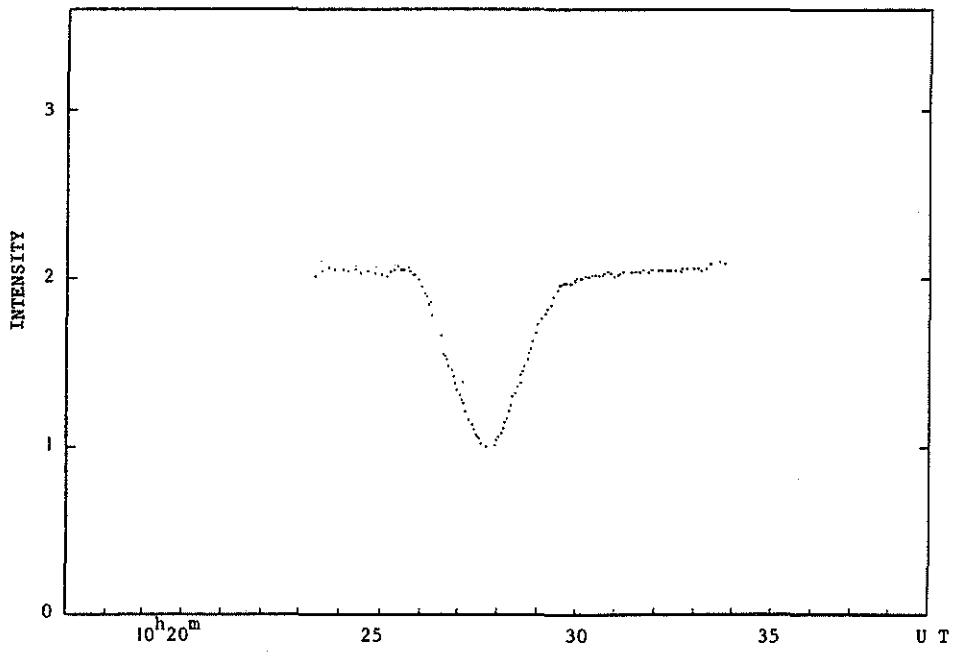

Figure 16. J2 eclipses J1 annularly on November 25, 1985 (Bisei)

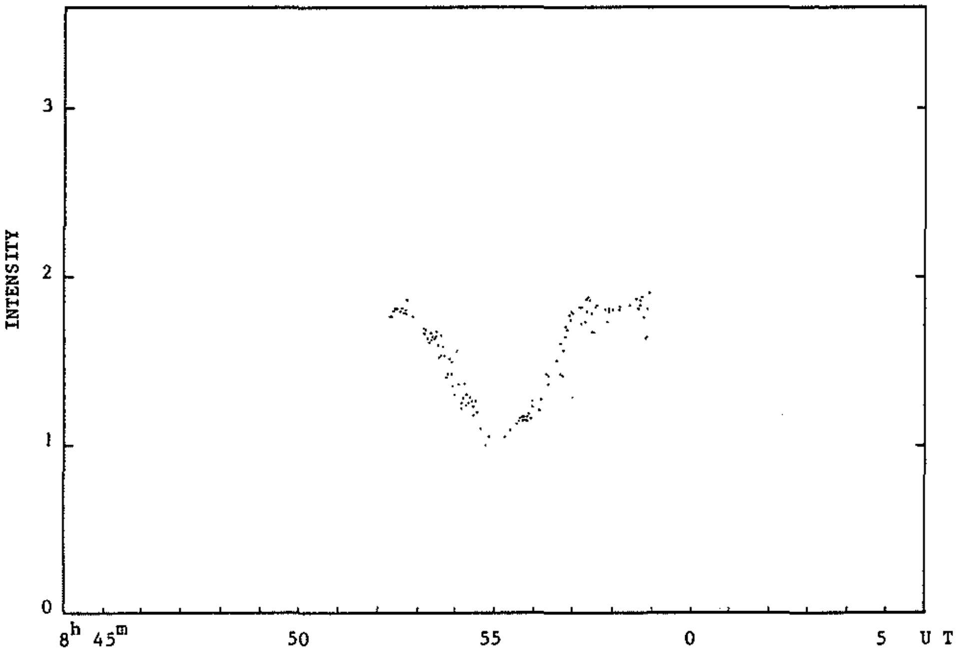

Figure 17. J1 occults J2 partially on December 15, 1985 (Simosato)

3. The midtimes of mutual phenomena

Although the obtained light curves have much information concerning such as albedo distribution and radius, we intend to correct only the longitude of three inner satellites in this paper using the midtime of each phenomenon.

In the case of partial phenomenon, because the light curve is nearly symmetrical, the light curve near midtime can be modeled on quadratic polinominal.

$$y(t)=a(t-t_0)^2+b \qquad \ldots\ldots(3)$$

where t_0 is the midtime.

We have made a linearized least squares differential fit to each light curve near midtime. Estimated midtime and their r.m.s. are listed in column 2 and 3 of table 3. Column 4 to 6 contain the residuals of each event. The letters O, E2, G5 and SV2 stand for "observed", "E-2 ephemeris", "G-5 ephemeris" and "SV2 ephemeris" (Vu, 1977; Sampson, 1921), respectively. The calculated midtimes of these three ephemerides are presented by Arlot (1984). Column 7 and 8 are the phase angles $\varphi(0^\circ<\varphi<180^\circ)$, which means Earth-Jupiter-the Galilean satellite angle for occultation and Sun-Jupiter-the Galilean satellite angle for eclipse. The mean error in this table is the formal error in the least squares procedure and may be larger in other midtime analysis methods. We omit some light curves of poor quality in this midtime analysis.

Table 3. The estimated midtimes

	Event			Midtime (TDT)							d (midtime)			Phase angle	
	No.	Observatory									O-E2	O-G5	O-SV2	φj	φk
			**				h	m	s	s	s	s	s	deg	deg
	1	3O1	B	1985	6	17	17	44	15.6	±1.5	−8.4	1.6	26.6	23.0	84.8
*	2	3O2	B		8	13	13	14	25.1	±1.8	9.1	16.1	2.1	38.3	99.2
	3	3O2	Sm		8	13	13	14	25.8	±0.8	9.8	16.8	2.8	38.3	99.2
	4	3E2	Sm		8	13	14	5	35.0	±0.6	−2.0	4.0	−7.0	38.5	97.6
*	5	3E2	B		8	13	14	5	40.0	±1.7	3.0	9.0	−2.0	38.5	97.6
*	6	3O2	B		8	20	16	22	26.8	±1.5	−4.2	3.8	−14.2	38.7	95.5
*	7	3E2	B		8	20	17	57	30.4	±2.3	−17.6	−12.6	−22.6	38.9	92.4
*	8	1O3	B		8	24	15	8	7.3	±2.2	16.3	15.3	9.3	57.3	160.5
	9	1O3	Sr		8	24	15	8	18.6	±1.2	27.6	26.6	20.6	57.3	160.5
*	10	1E2	Sm		9	3	10	54	18.5	±1.4	22.5	12.5	32.5	108.2	143.7
*	11	1E2	B		9	10	13	58	41.3	±0.9	6.3	−3.7	−8.7	98.4	141.9
	12	1E2	Sm		9	10	13	58	55.1	±1.2	20.1	10.1	5.1	98.3	141.9
*	13	1E2	Sm		10	12	13	34	8.3	±0.5	1.3	−3.7	−33.7	73.6	142.9
*	14	2E1	Sm		11	25	10	28	37.7	±0.9	−9.3	−9.3	−45.3	18.0	150.8
*	15	2E1	B		11	25	10	28	38.9	±1.2	−8.1	−8.1	−44.1	18.0	150.8
*	16	1O2	Sm		12	15	8	56	4.3	±1.6	11.3	3.3	−32.7	48.0	151.9

**B: Bisei, Sm: Simosato and Sr: Sirahama

4. The longitude corrections for inner three satellites

Because the precision of satellite ephemerides degrades most rapidly in the longitudinal direction, we correct longitude of each satellite at the epoch.

The observational equation is expressed as follows.

$$(a_k n_k \cos\varphi_k - a_j n_j \cos\varphi_j)\Delta T = a_j \cos\varphi_j \Delta l_j - a_k \cos\varphi_k \Delta l_k \quad \ldots\ldots (4)$$

where a_k is the semi major axis of the satellite k, n_j is the mean motion of the satellite j, ΔT is the residual of midtime and Δl_k is the longitude correction of the satellite k at the epoch. The eccentricity of the satellite is ignored in this equation. Since we cannot observe the mutual phenomena when the phase angle is neary 0 and since the coefficient of Δl_j in equation (4) becomes 0 when satellite j is at the maximum elongation from Jupiter, some selection effects may exist. It is desirable to observe many mutual events rather than to observe one event at many observatories.

We intend to correct the longitudes of only three inner satellites because the observed mutual phenomena of high quality involving J4 are quite few.

Figures from 18 to 22 are the observational equations in the phase space.

The obtained longitude corrections are shown in tables 5 and 6. We have tried two data sets, the one contains the whole 16 data, except for those with J4, the other contains the 11 data of comparatively high quality indicated as * in table 4. We show the estimated values by other authors in table 5 and 6, too. Aksnes & Franklin (1976) deduced the correction of longitudes using 91 light curves of mutual phenomena in 1973. Nakamura (1976) corrected the longitudes from 23 light curves.

Table 4. The estimated longitude corrections (Unit: 10^{-4} radian)

	Data set 1 (16 data)	Data set 2 (11 data)	Aksnes & Franklin (1976)	Nakamura (1976)
(E-2)				
J1	3.0 ±2.5	4.0 ±1.5		
J2	−1.0 ±0.6	−1.0 ±0.3		
J3	−0.1 ±0.4	0.0 ±0.9		
(G-5)				
J1	2.9 ±2.3	3.7 ±1.2		
J2	0.4 ±0.5	0.4 ±0.3		
J3	−1.0 ±0.3	−0.9 ±0.7		
(SV2)				
J1	24.9 ±3.4	26.7 ±1.4	22.7 ±1.0	19.0 ±0.7
J2	4.2 ±0.8	4.1 ±0.3	5.9 ±0.6	2.9 ±0.1
J3	−0.1 ±0.5	0.3 ±0.8	−2.5 ±0.3	−5.1 ±2.4

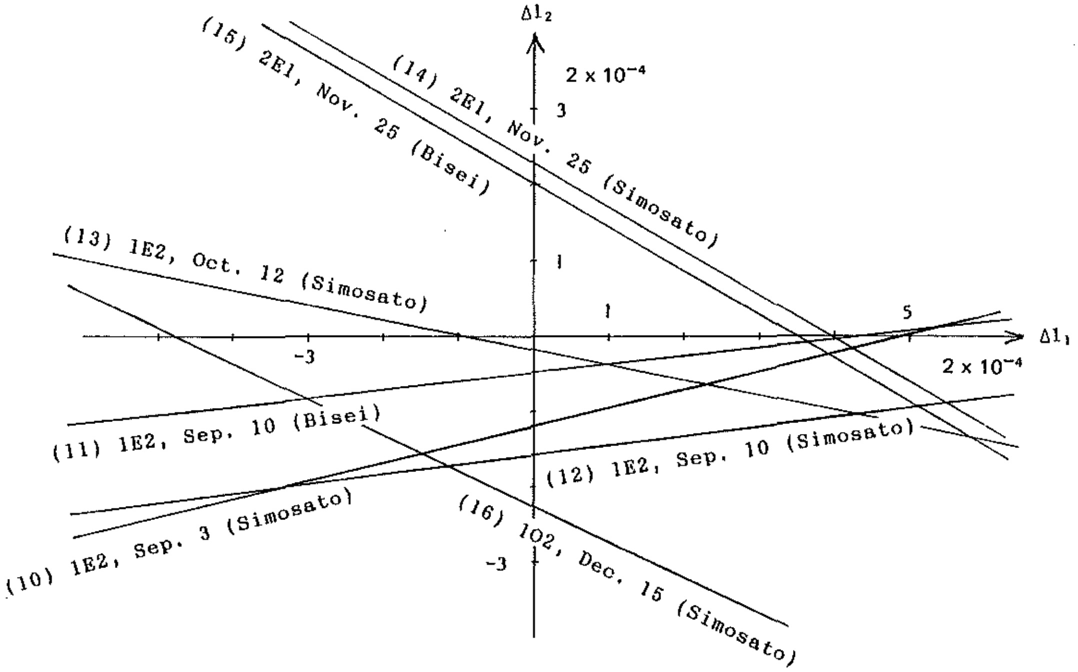

Figure 18. The longitude correction of J1 and J2 (E-2)

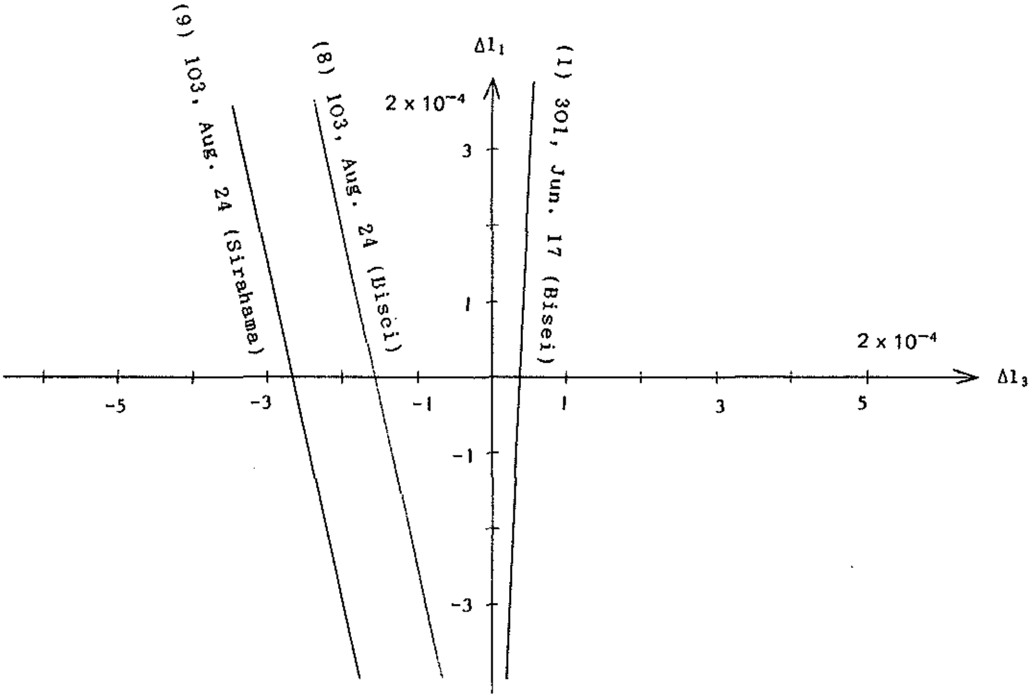

Figure 19. The longitude correction of J1 and J3 (E-2)

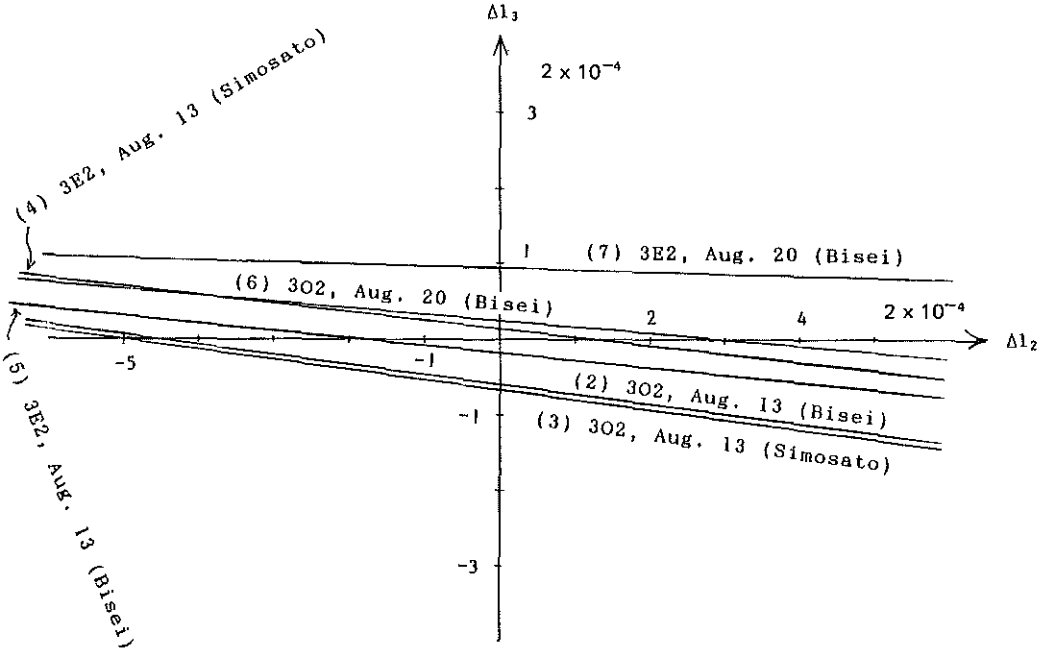

Figure 20. The longitude correction of J2 and J3 (E-2)

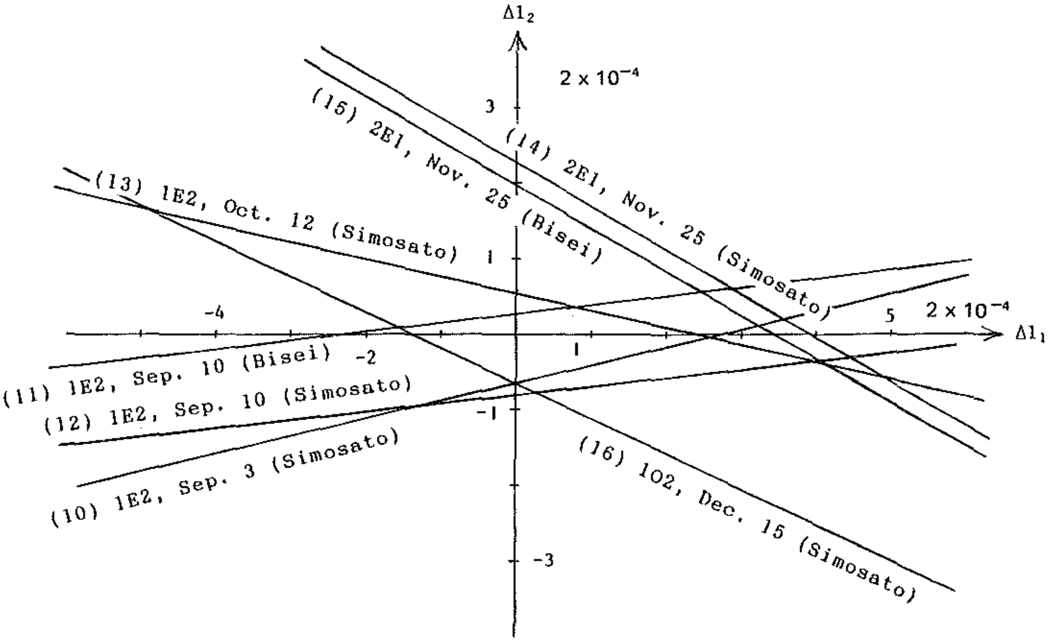

Figure 21. The longitude correction of J1 and J2 (G-5)

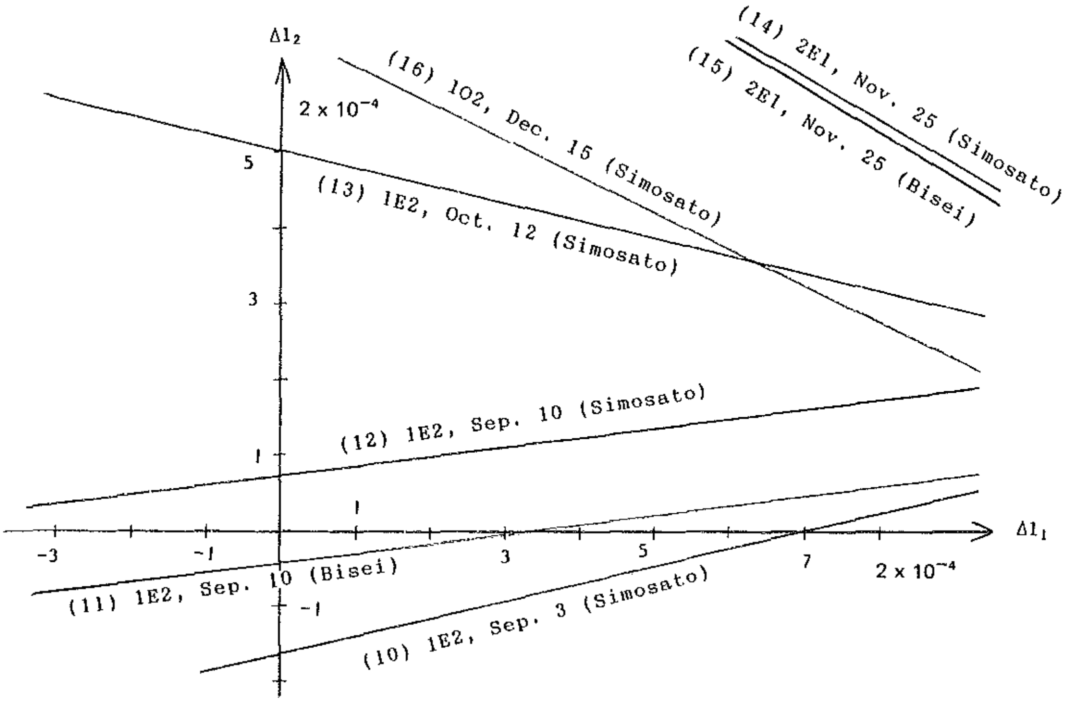

Figure 22. The longitude correction of J1 and J2 (SV2)

Table 5. The estimated time corrections (Unit: minuite)

Satellite	Data set 1 (16 data)	Data set 2 (11 data)	Aksnes & Franklin	Nakamura
(E-2)				
J1	0.12 ±0.10	0.16 ±0.06		
J2	–0.08 ±0.05	–0.08 ±0.03		
J3	–0.01 ±0.06	0.00 ±0.15		
Residual	0.15	0.08		
(G-5)				
J1	0.12 ±0.09	0.15 ±0.05		
J2	0.03 ±0.04	0.04 ±0.02		
J3	–0.16 ±0.05	–0.15 ±0.12		
Residual	0.13	0.07		
(SV2)				
J1	1.01 ±0.14	1.08 ±0.06	0.92 ±0.04	0.77 ±0.03
J2	0.34 ±0.06	0.33 ±0.03	0.48 ±0.05	0.24 ±0.01
J3	–0.02 ±0.08	0.05 ±0.14	–0.42 ±0.05	–0.83 ±0.40
Residual	0.20	0.08		

5. Discussions

Our results of J1 and J2 are mostly in accord with those of Aksnes & Franklin. The correction of longitude of J1 for E-2 and G-5 and the correction of J2 for E-2 seem to be significant. The difference between our results and other authors may arise from the absence in our analysis of the corrections of other augular variables such as ω or Ω. The absence of the corrections of these elements results from insufficiency of obtained data in 1985 to improve them. Therefore we restrict our attention to longitude corrections.

The error of the longitude of J1 is larger than other outer satellites in table 5. It is because the phase angle of J1 is always smaller than those of outer satellites and the coefficients of Δl_1 is always smaller. This is inevitable in the analysis of mutual phenomena. But the error of the midtime of the phenomena with J1 is comparable with those of others.

It is noteworthy that our results satisfy the Laplace relation within the estimation error for E-2 and G-5.

$$\Delta l_1 - 3\Delta l_2 + \Delta l_3 = 0 \qquad \ldots\ldots (5)$$

This seems to imply the accuracy of the amplitude of libration argument $(l_1 - 3l_2 + 2l_3)$ in E-2 and G-5 and to justify our analysis.

The difference between the results from the two data sets is smaller than the residuals.

If we gather world-wide light curves of mutual phenomena in 1973, 1979 and 1985, it will be possible to improve all the elements of the Galilean satellites and to investigate on the tidal secular accerelation of J1. We really hope that our observations enrich the knowledge on the satellite ephemerides.

6. Acknowledgements

We are most grateful to Dr. J. E. Lieske who kindly presented us the program of E-2 ephemeris and much information on the Galilean satellites. We also thank Mr. Fukusima who suggested us this observation campaign and offered us the the program to calculate planetary positions. We have also benefited from conversations with Dr. Nakamura and Dr. Souma.

Reference

Aksnes, K., Franklin, F.A. : 1976, Astron. J. **81**, 464
Arlot, J.E. : 1982, Astron. Astrophys. **107**, 305
Arlot, J.E. : 1984, Astron. Astrophys. **138**, 113
Lieske, J.H. : 1974, Astron. Astrophys. **31**, 137
Lieske, J.H. : 1980, Astron. Astrophys. **82**, 340
Nakamura, T. : 1976, Publ. Astron. Soc. Japan **28**, 239
Sampson, R.A. : 1921, Mem. Roy. Astron. Soc. **63**, 1
Vu, D.T. : 1977, Astron. Astrophys. Suppl. **30**, 361

ガリレオ衛星相互食(1985)の解析（要旨）

仙石 新，寺井 孝二，監物 邦男，淵之上清二
三宅 武治，西村 英樹，松本 邦雄，沢 雅行
佐々木弘志，内山 丈夫，村上 勝彦，金川 真一

木星の衛星であるガリレオ衛星の相互食が，1985年6月から12月にかけて，美星，下里，白浜の各水路観測所で観測された．14の現象が観測され23の光度曲線が得られた．

解析の結果，E-2 (Lieske, 1980) の理論に対する内側の3衛星の経度の補正は各々 $\Delta\ell_1 = 4.2\pm1.6(\times 10^{-4})$，$\Delta\ell_2 = -1.0\pm0.4(\times10^{-4})$，$\Delta\ell_3 = 0.0\pm1.0(\times10^{-4})$ と求まった．この成果はAksnes & Franklin (1976) の結果とほぼ一致している．