New Constants for Sampson-Lieske Theory of the Galilean Satellites from mutual occultations data

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Abstract

New constants for Sampson-Lieske theory of the Galilean Satellites have been derived using 6360 individual photographic positions (1891-1990) and 438 pseudo astrometric positions from mutual occultations during 1973, 1979, 1985 and 1991. Using these new sets of constants, although no significant improvement is noticed in the O-C values of the sky plane co-ordinates compared to G5 and E 2×3, residuals in longitude for Io and Euyropa are found to improve. Problems concerning the inclusion of mutual event data in attempting evaluation of secular variations of the mean motions of the satellites are discussed.

Keywords : Galilean Satellites - Mutual occultations - ephemerides - Jupiter

1. Introduction

The constants of motion of the Galilean Satellites are now efficiently updated using Lieske's (1974, 1977) technique by computing the corrections (ε, β) to the basic sets of constants. Lieske progressively updated these constants from E1 (Lieske, 1978) using the eclipse data of 1878-1903 to E2 (Lieske, 1980) by supplementing visual eclipses between 1903 and 1972, photographic data between 1967 and 1978, and mutual events of 1973. The E2x3 (Lieske, 1987) ephemeris was derived by further additions of more mutual event pairs from 1973 and 1979, 183 pairs of data from Voyager optical navigation images and 15711 classical eclipses from 1652-1983. Arlot (1982, hereafter paper I) used 8856 individual photographic observations between 1891 to 1978 to derive the G5 ephemeris. The present investigations relate to determinations of a new sets of constants using photographic data between 1891 to 1990 and astrometric positions derived from mutual occultations during 1973, 1979, 1985 and 1991.

2. The observational material

2.1 The photographic data

Most of the photographic data that were used in paper I. were utilized in this study. Additional excellent unpublished photographic material covering the period between 1986 and 1990 (Pascu, 1992) have been included. Table 1 gives the details of the photographic observations.

2.2 The mutual occultation data

Two sets of mutual occultation data were used. The data set (1) contains the astrometric positions derived by Descamps and Thuillot (1993), and Descamps (1992, 1994) from the mutual occultation light curves of 1985 and 1991 assuming Hapke's light scattering law for a macroscopically rought surface (Hapke, 1984). The data set (2) consists of astrometric positions derived from the mutual occultation light curves of 1985 (Arlot et al. 1992) and 1991 (Arlot et al, 1991) using the model by Vasundhara (1993). While Lommel-Seeliger's law was considered adequate for the light curves of Io during 1991, the Hapke's parameters derived by Descamps and Thuillot were (1992) used for rest of the light curves. The published astrometric positions of 1985 (GSO and Franklin, 1991) which were derived using Lambert's law were reconstructed to adopt Hapke's law and included in Set (2). Both sets (1) and (2) contain reconstructed values of the published positions of 1973 (Aksnes and Franklin 1976) and 1979 (Aksnes et al. 1984), to account for the phase corrections (Aksnes, Franklin and Magnusson 1986). Tables 2(a & b) give the statistics of the events for these two data sets.

3. Corrections to the constants

The method developed in paper I has been used in the present study. Since the mutual occultations provide relative position of the two satellites, positions of the satellites in the photographic data set were also considered with respect of their center of mass. If Ci (i = 1, 29 for ε, and i = 1 to 22 for β) are the constants of motion, Q_o and Q_c the observed and calculated sky plane positions X or Y, and $\frac{\partial Q}{\partial C_i}$ the partial derivatives of these observables with respect to C_i we have

$$Q_o - Q_c = \Sigma_i \frac{\partial Q}{\partial C_i} \triangle C_i$$

The inherent accuracies of the photographic observations with long focal length instruments were included as in Paper I in an implicit manner as by considering the angular distances in microns instead of arcsecs. The weights of observations of Helsingfors (1891-1897) and Pulkovo (1895-1898, 1904-1910) were increased twofolds since each of their observations corresponds to several exposures on a plate. The mutual occultations have residuals of about 0.02 arcsec and therefore were assigned weights of 50. The constants that were updated were the mean motions ($\varepsilon_6 - \varepsilon_8$), primary eccentricities ($\varepsilon_{16} - \varepsilon_{19}$), primary sine inclinations ($\varepsilon_{21} - \varepsilon_{24}$), mean longitudes ($\beta_1, \beta_2, \beta_4$), proper perijoves ($\beta_6 - \beta_9$), proper nodes ($\beta_{11} - \beta_{14}$), libration amplitude ($\epsilon_9$) and the libration phase angle (β_5). The starting ephemeris for the initial run was E1, three more iterations were carried out by progressively adjusting the (ϵ, β) values. The resulting set of (ϵ, β) values labled I-32 and another set of constants I-33 derived by assigning a weight of 10 to the mutual occultation data sets are given in table 3 along with G5 for comparison.

The (O-C) in the sky plane co-ordinates of the four satellites from their centre of masss are shown in Fig.1 (a-b) using I32, Fig.2 (a-b) using I33, Fig.3 (a-b) using G5 and

Fig.4 (a-b) using E2×3. The r.m.s. of the residuals in the sky plane co-ordinates calculated using the expression.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} \sum_{j=i}^{4} [(\times_i^j)^2 + (Y_i^j)^2}{2 \times 4 \times N}}$$

are given in Tables [1,2 (a & b)] for the four ephemerides, where j refers to the satellites and i the running index of the data point.

4. (O - C) in longitude

The error in the longitude of the satellite using G5, I32 and E2×2 ephemerides are given table 4. The residuals in longitudes were computed by considering (i) only the photographic (Ph) data (ii) Photographic and mutual event data (Ph+ME) weighted as 50. The errors in for Callisto have increased using I32 because of limited number of mutual event observations for this satellites.

The (O-C) of the individual data point from 1891 through 1991 were analysed to look for co-efficient of the T^2 terms. The derived values of $\dot{n}/n$ using I32, I33, G5 and E2×3 are given in Table 5. Since the weight for the ME data set for determination of I33 was set to 10, only the same has been used for determining the $\dot{n}/n$ values.

5. Results and discussions

The (O-C) in the sky plane, co-ordinates of the satellites in Figs (1-4) and Tables (2a & b) clearly justify higher weights of 50 for the ME data set. Effects of inclusion of the ME data set lowers the longitude residual compared to G5 and E2×3 for J1 and J3 (Table 4). The new sets of constants in I32 produce significantly lower residual for J1 but not for the other satellites. A curious trend for J2 is noticed in the estimates of $\dot{n}_2/n_2$. G5, derived from most of the photographic data of the present analysis sans the ME data sets leads to a positive value for $\dot{n}_2/n_2$ whereas I32 and I33 derived after including the ME data indicate decelaration of Europa (Table 5). Again, both G5 and E2×3 ephermerides yield progressively negative values for $\dot{n}_2/n_2$ when the weight of ME data set is increased. Excellent photographic data by Pascu during 1974-1990 with residuals only 3-5 times that of the ME but outnumbering in number and spanning almost the same period yield a positive $\dot{n}_2/n_2$. This apparent deceleration of J2 when ME data set is used may therefore be due to of the unexplained progressively increasing longitude residuals of -12 km, -95 km, - 211 km and -308 km during 1973, 1979, 1985 and 1991 respectively (Mallama, 1992). Predominance of the J1-J2 events and limited longitude coverage during a mutual event season preclude reliable estimation of the secular changes in the mean motion of the Galilean Satellites. A larger data set consisting of the mutual eclipses and the data from the forthcoming mutual event season in 1996-1997 could help in resolving this apparent deceleration of Europe in the ME data set.

Acknowledgements.

We would like to thank Dr.J.H.Lieske from JPL for the computer codes for calculating the revised Sampson theory. We are indebted to Dr.D. Pascu from USNO for allowing us to use his yet unpublished excellent data of 1986-1990.

Fig. Captions: (O – C) in $\Delta\alpha\cos\delta(a)$, $\Delta\delta(b)$ relative to the center of mass of the observed satellites. The filled triangles and crosses correspond to photographic and mutual event data sets respectively.

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Table 3(a) ε values for I32 and I33 and G5 ephemerides[1]

ϵ	I 32	I 33	G 5
1	(0.041590 ± 0.0098)		
2	(-0.002461 ± 0.0200)		
3	(-0.231890 ± 0.0076)		
4	(0.256938 ± 0.0084)		
5	$(\{2.067082138 \pm 0.095\}.10^{-4})$		
6	$\{0.1944073 \pm 0.070235\}.10^{-8}$	$\{0.2113185 \pm \}.10^{-8}$	$\{-0.1835945 \pm 0.08513\}.10^{-8}$
7	$\{1.0642537 \pm 0.044510\}.10^{-8}$	$\{0.11012828 \pm\}.10^{-8}$	$\{-0.1054947 \pm 0.05523\}.10^{-8}$
8	$\{-4.3848824 \pm 0.122708\}.10^{-8}$	$\{-4.4122061 \pm\}.10^{-8}$	$\{-5.5560148 \pm 0.15354\}.10^{-8}$
9	$\{14.0045547 \pm 0.644048\}.10^{-4}$	$\{14.1673386 \pm\}.10^{-4}$	$\{14.9959 \pm 0.086918\}.10^{-4}$
10	$(\{0.1620 \pm 0.0633.10\}^{-4})$		
11	(-0.007778 ± 0.00054)		
12	(-0.275934 ± 0.024)		
13	(-0.000308 ± 0.0006)		
14	$(\{0.0950 \pm 2.80\}.10^{-4})$		
15	(0.00 ± 0.15)		
16	-0.7697975 ± 0.070239	$-0.8137604 \pm$	-0.473172 ± 0.098801
17	-1.0132804 ± 0.060432	$+0.8728083 \pm$	$+0.463707 \pm 0.108628$
18	-0.0547743 ± 0.0033858	$-0.0545148 \pm$	-0.043680 ± 0.004671
19	-0.0019453 ± 0.000415	$-0.0017829 \pm$	-0.003586 ± 0.000542
20	(0.002781 ± 0.0005)		
21	$+0.4601799 \pm 0.040741$	$+0.4752529 \pm$	$+0.492066 \pm 0.060640$
22	-0.0093312 ± 0.001389	$-0.0092887 \pm$	-0.006578 ± 0.002110
23	$+0.0484492 \pm 0.002269$	$-0.0485697 \pm$	$+0.050194 \pm 0.003248$
24	-0.0784726 ± 0.000910	$-0.0784863 \pm$	-0.070668 ± 0.001315
25	(0.005384 ± 0.011)		
26	(-0.000133 ± 0.0011)		
27	$(\{0.0 \pm 0.0047\}.10^{-4})$		
28	$(\{0.0 \pm 0.0010\}.10^{-4})$		

[1] Parameters within the paranthesis were not determined.

Table 3(b) β values for I 32, I 33 and G 5 ephemerids[1]

β	I 32	I 33	G 5
1	(0.042583 ± 0.004717	0.046863	0.046245 ± 0.04819
2	-0.014971 ± 0.000945	-0.013741	-0.014445 ± 0.000877
3	–	–	–
4	-0.068665 ± 0.000273	-0.068782	-0.066536 ± 0.000443
5	182.841072 ± 0.003566	182.824371	182.797225 ± 0.005084
6	81.1687813 ± 21.2911	58.811159	62.231560 ± 7.608520
7	86.778098 ± 2.060911	87.679983	86.403965 ± 4.320290
8	14.487234 ± 0.185102	14.621422	14.181513 ± 0.236000
9	-0.689518 ± 0.023084	-0.698253	-0.747260 ± 0.028121
10	(0.166755 ± 0.05)		
11	62.922453 ± 1.529083	63.057544	60.834877 ± 3.490252
12	5.785080 ± 0.084104	5.827361	6.075500 ± 0.125467
13	-5.423444 ± 0.128188	-5.305660	-5.450563 ± 0.210661
14	4.468647 ± 0.055347	4.447649	+4.903778 ± 0.077832
15	(-0.233589 ± 0.19		
16	(0.0 ± 0.4		
17	(-0.140391 ± 0.03)		
18	(15.610 ± 3.1		
19	(5.135 ± 4.2)		
20	(-1.719 ± 2.1)		
21	-7.784 ± 1.8)		
22	(0.4428 ± 0.007		

[1] Parameters within the paranthesis were not determined.

Table 1 : Details of photographic data

Observer	Observatory	Year	No. of positions J1	J2	J3	J4	Residual (arcsec) G-5	I-32	I-33	E2×3
Renz	Helsingfors	1891					0.117			
Renz	Helsingfors	1892-1897	171	175	184	174		0.110	0.111	0.114
Renz	Pulkovo	1895-1898								
Balanovsky	Pulkovo	1904-1910								
Chevalier	Zo-Se	1917/1918	132	132	133	121	0.148	0.151	0.151	0.158
De Sitter	Greenwich	1918/1919								
De Sitter	The Cape	1924								
Petrescu	Bucarest	1934	85	104	106	118	0.217	0.223	0.222	0.226
Petrescu	Paris	1936								
Van Biesbrock	Yerkes	1961-1963								
Gorel	Nicolaiev	1962-1966								
Soelie	Bordeaux	1966-1974								
Gorel	Nicolaiev	1973-1974	284	282	318	307	0.390	0.390	0.390	0.391
Debehogne	Rio de Janeiro	1977/1978								
"	Uccle	1977/1978								
"	La Silla	1977/1978								
Ianna et al	Mc Cormick	1977/1978	70	100	95	108	0.104	0.104	0.104	0.107
Pascu	Mc Cormick	1967/1968	88	87	89	95	0.095	0.095	0.095	0.096
"	USNO (Wash.)	1973	72	65	62	67	0.110	0.111	0.111	0.112
"	"	1974	107	115	120	123	0.082	0.085	0.085	0.084
"	"	1975-1977	107	116	109	119	0.085	0.086	0.086	0.086
"	"	1977/1978	59	59	53	59	0.102	0.103	0.103	0.104
Pascu[1]	"	1986	84	74	82	80	0.077	0.074	0.074	0.077
"	"	1987	116	133	129	133	0.074	0.071	0.071	0.074
"	"	1988/1989	52	54	60	60	0.059	0.056	0.056	0.061
"	"	1990	79	72	84	96	0.068	0.067	0.067	0.069

[1] Private communications

Table 2(a) Details of mutual occultation data set (1)

Year	Total	No. of positions				Residual (arcsec)			
	events	J1	J2	J3	J4	G5	I32	I33	E2×3
1973	21	20	21	1	0	0.022	0.019	0.019	0.018
1979	3	1	3	2	0	0.006	0.008	0.008	0.010
1985	23	11	14	15	6	0.019	0.020	0.020	0.022
1990-91	34	29	34	5	0	0.036	0.029	0.030	0.032

1. Source : Decamps (1992a)

Table 2(b) Details of mutual occultation data set(2)

Year	Total	No. of positions				Residuals (arcsec)			
	events	J1	J2	J3	J4	G5	I32	I33	E2×3
1973[1]	27	25	27	2	0	0.011	0.009	0.009	0.011
1979[2]	4	3	4	1	0	0.012	0.013	0.013	0.013
1985[3]	16	7	9	10	6	0.022	0.022	0.023	0.021
1985[4]	71	52	41	56	21	0.025	0.025	0.026	0.023
1990-91[5,6]	20	16	19	4	1	0.034	0.027	0.028	0.032

Sources :

1. Aksnes and Franklin, 1976
2. Aksnes et al., 1984
3. Arlot et al., 1992
4. Franklin and GSO, 1991
5. Vasundhara, 1994
6. Arlot et al., 1995

Table 4 : Error in Longitude (min of time)

Data set	J1	J2	J3	J4	Ephem.
Ph	0.060 ± 0.011	0.009 ± 0.012	0.053 ± 0.015	0.073 ± 0.020	G5
Ph+ME	0.058 ± 0.010	-0.021 ± 0.011	0.041 ± 0.014	0.076 ± 0.019	G5
Ph	0.019 ± 0.011	0.039 ± 0.012	0.078 ± 0.015	0.201 ± 0.020	I32
Ph+ME	0.018 ± 0.010	0.017 ± 0.011	0.067 ± 0.014	0.203 ± 0.019	I32
Ph	0.041 ± 0.011	0.057 ± 0.013	0.165 ± 0.016	0.042 ± 0.020	E2×3
Ph+ME	0.038 ± 0.010	0.033 ± 0.011	0.157 ± 0.014	0.035 ± 0.019	E2×3
Ph	1508	1568	1624	1660	Data points
Ph+ME	1508 + 153	1568 + 170	1624 + 88	1660 + 27	Data points

Table 5 : Secular accelerations of the Satellite Io-Ganymede

Data	J1 $\dot{n}_1/n_1 \times 10^{11}$	J2 $\dot{n}_2/n_2 \times 10^{11}$	J3 $\dot{n}_3/n_3 \times 10^{11}$	Ephemeris
Ph	24.69 ± 7.89	-6.08 ± 9.29	16.02 ± 11.15	I32
Ph+ME (50)[1]	22.02 ± 7.48	-25.26 ± 8.42	10.56 ± 10.64	I32
Ph+ME(10)[2]	24.56 ± 7.62	-7.04 ± 8.96	15.77 ± 10.78	I32
Ph	24.28 ± 7.89	-4.49 ± 9.29	14.52 ± 11.15	I33
Ph+ME(10)	24.13 ± 7.62	-5.15 ± 8.96	14.26 ± 10.78	I33
Ph	27.34 ± 7.91	11.11 ± 9.31	3.89 ± 11.18	G5
Ph+ME(50)	24.57 ± 7.29	-12.69 ± 8.44	-0.22 ± 10.67	G5
Ph+ME(10)	27.19 ± 7.64	9.91 ± 8.98	3.69 ± 10.08	G5
Ph	32.92 ± 7.94	26.14 ± 9.35	-28.86 ± 11.23	E2×3
Ph+ME(50)	29.69 ± 7.53	-2.71 ± 8.48	-30.66 ± 10.71	E2×3
Ph +ME(10)	32.75 ± 7.67	24.72 ± 9.02	-28.96 ± 10.85	E2×3

1. Weight assigned for the mutual event set = 50
2. Weight assigned for the mutual event set = 10