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Astrometry from CCD photometry of mutual events of Jovian satellites from VBO during 1997

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Abstract. Astrometric results of CCD observations of the mutual events of the Galilean satellites of Jupiter from the Vainu Bappu Observatory are presented. The shifts in the photo-centers on the disks of Io and Europa due to albedo variations inferred from the available mosaics of Galileo imagery are determined. The estimated shifts from ≈90 km East to ≈50 km West on Io and from ≈50 km East to ≈30 km West for Europa during one orbital period are comparable to the accuracies provided by the present-day ephemerides. In a given mutual event series, the mutual events involving a given satellite pair dominate in number and occur nearly at the same orbital longitude within $\pm 20°$; all the events are therefore delayed or all of them advanced depending on the direction of the shift of the photo-center. The implications of including these cumulative and sustained longitude residuals on the constructed ephemerides are discussed.

Key words. eclipses – astrometry – ephemerides – occultations – planets and satellites: general

1. Introduction

The Galilean satellites occult and eclipse each other twice during the orbital period of Jupiter of about 11.6 years. The astrometric results of mutual events that provide accuracies of the order of $0\farcs03$ have great potential in studies of secular variations in mean motion of the satellites. To this date, there is no consensus on the derived value of $\dot{n}_1/n_1$ by various researchers (Aksnes & Franklin 2001; de Sitter 1928; Goldstein & Jacobs 1986; Goldstein & Jacobs 1995; Greenberg et al. 1986; Lieske 1998; Vasundhara et al. 1996). A small negative value was estimated by Lieske (1998) while the results of other authors indicate a positive value. Aksnes & Franklin (2001) used 514 light curves of the mutual events between 1973 and 1991 and six light curves of the recent series in 1997 to show that $\dot{n}_1/n_1$ is likely to have a positive value between 2.5×10^{-10} yr^{-1} and 4×10^{-10} yr^{-1}. Further inputs for studies of this kind using the astrometric data from the 1997 series will help in better constraining the $\dot{n}/n$ values of the satellites. We present here the astrometric results of the observations of the mutual events from the Vainu Bappu observatory (VBO, 78°49$'$.58 E, 12°34$'$.58 N, 725 m) during 1997, that may be directly utilized for further upgrading the ephemerides. Kaas et al. (1999) investigated the residuals in the differential sky plane coordinates, $\Delta\alpha \cos\delta$ and $\Delta\delta$ with respect to the E3 and E5 ephemerides. These authors point out that from an albedo map of Io derived by A. McEwen from the 1979 Voyager encounters, J. Goguen concluded that an extensive bright region on Io can displace the satellite's photo-center and geometric-center by about 130 km. Motivated by this, we carried out the present work by using the albedo mosaics of Io and Europa constructed from Galileo images by Geissler et al. (1999) and Phillips et al. (1997) respectively. We investigate, in a semi-quantitative manner, the possible effects on the ephemerides, constructed from (O–C) in longitudes that were not corrected for the shift of the photo-center.

2. Observations

The observations were carried out at the cassegrain focus of the 102 cm Carl Zeiss reflector and at the prime focus of the 234 cm Vainu Bappu Telescope at the observatory using liquid nitrogen-cooled CCDs. Only a limited region on the CCD frame containing the satellites was read to save on the read-out time. The sampling intervals at the 234 cm telescope ranged between 4–9 s. The duration of this interval mainly depended on the time needed by the PC-based data acquisition system to read the selected window. A locally-developed macro permitted automated capturing of the frames and reading the starting time from the GPS clock. The time written in the header of an image is accurate to a few milliseconds. At the 102 cm telescope,

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Table 1. Astrometric results of the 1997 events observed from VBO.

DATE Tel[1], F[2]	Event	EPH.	T_g^{Fit} UT	ΔX km	Y km	(O–C)Y km	$\Delta\alpha\cos(\delta)$ km	$\Delta\delta$ km	*CML* Deg	Q
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
02 May 97	2E1	E5	22 38 17.9	154 ± 1480	-3017 ± 147	322	1053	−2827	305.0	3
CZ, R		E3		-30 ± 1480	-3016 ± 150	310	1053	−2826		
12 Jul. 97	2E1	E5	20 47 38.1	104 ± 248	1968 ± 195	138	−694	1841	337.7	7
VBT, NB		E3		1 ± 251	1965 ± 188	119	−693	1838		
15 May 97	3O1	E5+M	20 59 52.4	314 ± 63	-2292 ± 82	276	813	−2143	55.5	5
VBT, NB		E5		368 ± 181	-2389 ± 82	178	847	−2234		
		E3		453 ± 181	-2388 ± 83	178	847	−2233		
11 Nov. 97	3E1	E5	15 47 35.4	283 ± 227	3682 ± 307	74	−1190	3485	286.2	5
CZ, R		E3		271 ± 227	3690 ± 306	92	−1192	3492		
29 May 97	3O2	E5+M	23 07 14.1	-155 ± 18	1172 ± 78	−239	−420	1094	54.6	25
VBT, NB		E5		-141 ± 19	1231 ± 59	−179	−441	1150		
		E3		-82 ± 19	1236 ± 75	−190	−443	1154		
18 Jul. 97	3E2	E5	18 56 52.2	-92 ± 22	$-3431. \pm 23$	−35	1202	−3214	68.1	20
CZ, V		E3		-26 ± 22	-3431 ± 25	−44	1202	−3214		
23 Aug. 97	3E2	E5	14 03 30.3	99 ± 89	$-3234. \pm 63$	−18.0	1069	−3052	101.4	9
CZ, V		E3		180 ± 89	-3234 ± 63	−14	1069	−3052		
22 Sep. 97	3E2	E5	19 02 09.8	-77 ± 34	2126 ± 91	−27	−672	2017	286.4	19
CZ, O		E3		-29 ± 34	2125 ± 92	−31	−672	2016		
11 Nov. 97	3O2	E5+M	15 38 23.5	-124 ± 21	[36][3]	−423	−10	35	298.8	6
CZ, R		E5		-97 ± 21	[−37]	−496	10	−36		
		E3		-18 ± 21	[−33]	−500	9	−32		
01 Aug. 97	4E2	E5	20 11 47.8	-396 ± 10	3367 ± 41	−25	−1155	3163	54.3	24
VBT, NB		E3		-590 ± 30	3368 ± 37	−41	−1155	3164		
11 Sep. 97	1E3	E5	16 30 12.6	154 ± 16	-1321 ± 107	−149	423	−1251	30.0	20
CZ, V		E3		167 ± 16	-1322 ± 110	−141	423	−1253		

1. Tel: VBT = 234 cm Vainu Bappu telescope, CZ = 102 cm Carl Zeiss telescope.
2. F: Filter, NB = Narrow Band filter 5141 Å (118 Å), O = No filter, V & R = Standard broad band filters.
3. Total event.

the time was read from the system clock. As this clock was set manually, the sampling times of this data set are accurate to $\pm 0\farcs5$. However, the main source of error in fitting the time of light minimum comes from the scatter in the data points due to photometric noise. Further, at this telescope the series of frames were acquired by giving the commands manually. The sampling interval of this data set was therefore in the range 7–15 s. The telescope and the details of the filters are given in Col. 1 of Table 1. Care was taken whenever possible to include a third satellite in case of occultations or the eclipsing satellite in case of eclipses in the data acquisition window. Although several events were recorded, only those for which the differential photometry could be carried out were found to be usable. During the occultation events, the two satellites merge in the CCD frame. The field was imaged about an hour before and/or after the event to get their individual flux measurements. Further details of the observations and reductions are discussed in an earlier paper (Vasundhara et al. 2001). These light curves are available at the website of L'Institut de mécanique céleste et de calcul des éphémérides[1].

3. Model fit to the light curves

3.1. Fit to the 1997 data set

The light curves were fitted using an earlier model (Vasundhara 1991, 1994) after modifying to take into account the albedo variations on the surface of the satellites. The Joviocentric position and the velocities were computed using E3 (Lieske 1991) and E5 (Lieske 1998) sets of corrections to the Sampson Lieske theory (Lieske 1977). The present study uses the mosaics of Io constructed by Geissler et al. (1999) through green and the

[1] `ftp://ftp.bdl.fr/pub/NSDC/jupiter/raw_data/phenomena/mutual/`

NIR filters which are simple cylindrical map projections at 5 km/pixel or 6.343923092 pixel/degree and have a linear contrast stretch such that digital numbers from 0 to 255 represent radiance factors from 0 to 1.2. The values are appropriate for a phase angle of 14 degrees. Hapke's photometric function with correction for macroscopic roughness (Hapke 1984) was used to describe the limb darkening on the satellite for the occultation events. The values of the Hapke's parameters were adopted from McEwen et al. (1988). The mosaic of Europa at 8m/pixel resolution down loaded from the website of the United States Geological Survey, Astrogeology Program, Flagstaff, Arizona[2], was used. This global map base of Europa was created by Phillip et al. (1997) by utilizing the best image quality and moderate resolution coverage supplied by Galileo SSI (Solid State Imaging instrument) and Voyager 1 and 2. The Hapke's parameters for this satellite were taken from Domingue & Verbiscer (1997). During the fitting process, the gaps in the mosaics in the polar regions were filled using the median values from the neighboring latitude regions. For the eclipse events, the gradient of the penumbral intensity plays a more dominant role in determining the shape of the light curves than the albedo variations. These light curves were therefore modeled assuming uniform albedo and a smooth photometric function (Hapke 1981) to evaluate the limb darkening.

The fitted astrometric results for different sets of events are given in Table 1. The date of the event is given in Col. 1. The event types are given in Col. 2. Following the normal practice of designating the events, the code 2E1 indicates that Europa eclipses Io. Similarly, 3O2 denotes the occultation of Europa by Ganymede For occultations, E5+M corresponds to E5 with albedo variations inferred from the Galileo mosaics. For both occultations and eclipses, E5 and E3 represent the results using the corresponding ephemerides without considering the albedo maps. The model light curve was slided along the time axis to match the observed light curve. This time shift and the impact parameter were derived as free parameters in the least square fit. The model also takes into account the intensity variation on the surface of the satellite due to phase effects (Aksnes et al. 1986). The fitted time shift is a direct measure of the delay/advance in longitude at the time of geometric conjunction and accounts for the phase effects in case of fits using E5 and E3. For the fits using E5+M, the time shift in addition, accounts for the shift in the photo-center from the geometric-center of the satellite due to albedo variations on its surface. This required shift ΔX in km is given in Col. 5. The time $T_g^{\rm Fit} = T_g^{\rm Pred} - \Delta X/v$ in Col. 4 gives the fitted time of close approach of the geometric centers of the two satellites for occultations and the time of close approach of the eclipsed satellite to the shadow center for eclipses. In the above expression, v is the velocity of the occulted (eclipsed) satellite relative to the occulting (eclipsing) satellite. Column 6 gives the fitted impact parameter, Y. Column 7 gives the (O–C) in the impact parameter. The differential sky plane coordinates $\Delta\alpha\cos\delta$ and $\Delta\delta$ in the sense (S2–S1) in km are given in Cols. 8 and 9 respectively. The central meridian longitude (CML) of the occulted/eclipsed satellite, geocentric for occultations and heliocentric for eclipses are given in Col. 10. An index of the quality of the light curve is given in Col. 11, which is evaluated based on the quantity $Q = (I_0 - I_{\rm min})/\sigma_{I_0}$, where, σ_{I_0} is the standard deviation of the intensity I_0 outside the event and $I_{\rm min}$ is the intensity at the light minimum. The astrometric parameters in Cols. 8 and 9 at the time $T_g^{\rm Fit}$ can be directly used as astrometric inputs for improving the constants of motions of the satellites.

For the 3O2 events on 29 May and 11 November 1997, the longitude corrections increase marginally if albedo variations are taken into account using E5. For all the 3O2 and 3E2 events except for the incomplete light curve of 23 August 1997, the longitude corrections with respect to E3 interestingly are lower compared to those with respect to E5 by ≈65 km. This comes as a surprise as E5 was constructed by Lieske (1998) by including a large number of satellite pair positions of mutual event series of 1973, 1979, 1985 and 1991, while E3 used only those of 1973 and 1979. To further compare E5 and E3, and also to investigate the effect of inclusion of realistic albedo variation in the model (E5+M), we re-estimate the astrometric positions from some sample light curves of the two extensively observed mutual events series, 2O1 during 1991 and 3O2 during 1985 using the present model in the following sections.

3.2. The 2O1 events of 1991

The published light curves of 2O1 events of 1991 (Arlot et al. 1996; Mallama 1992; Vasundhara 1994) were fitted using the present model. The NIR (0.757 μm) mosaic was used for the VBO observations of 1991 through I filter. The green (0.560 μm) mosaic was used for the V filter observations. A comparison of fitted light curves using E5+M (upper panel) and E5 (lower panel) is shown in Fig. 1 for the 2O1 event on 16 February, 1991. The uncertainty in the flux measurement corresponding to the data points outside the event is shown. An improvement in the fit is noticed in case of E5+M compared to E5, especially in the wings and the deep region of the light curve. The fitted parameters are given in Table 2. As pointed out by Kaas et al. (1999), the residuals are lower compared to E5 than compared to E3. This is expected as this data set was used for constructing E5. Figure 2 shows the longitude residuals in km verses the central meridian longitude. Open circles, filled circles and crosses denote O–C in longitude with respect to E3, E5 and E5+M respectively. For the eclipses of the same series, open and filled squares correspond to E3 and E5 respectively. The O–C in longitude with respect to E5 is lower compared to E3 and is lowest in the case of E5+M. The open and filled triangles represent

[2] http://wwwflag.wr.usgs.gov/USGSFlag/Space/Jupiter/Mosaics/europa/

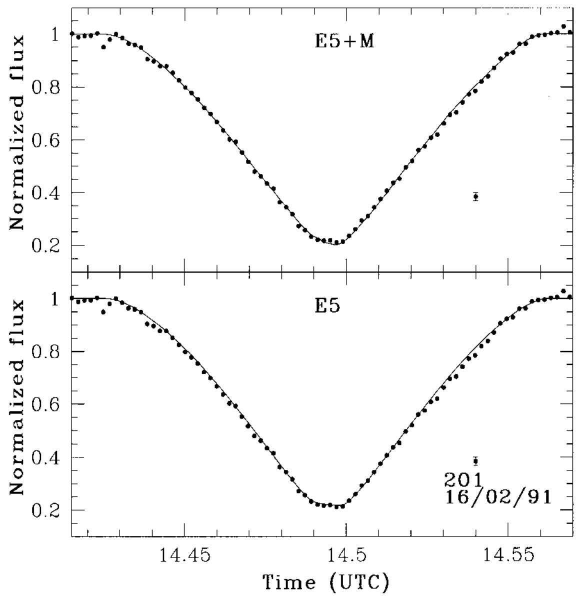

Fig. 1. The 2O1 event on 16 February, 1991. Above: fit using E5 and albedo variations inferred from the NIR mosaic of Io (Geissler et al. 1999). Below: fit using E5 and assuming a uniform surface for Io. For both the fits, Hapke's parameters by McEwen et al. (1988) have been used to model the limb darkening on the disk of Io.

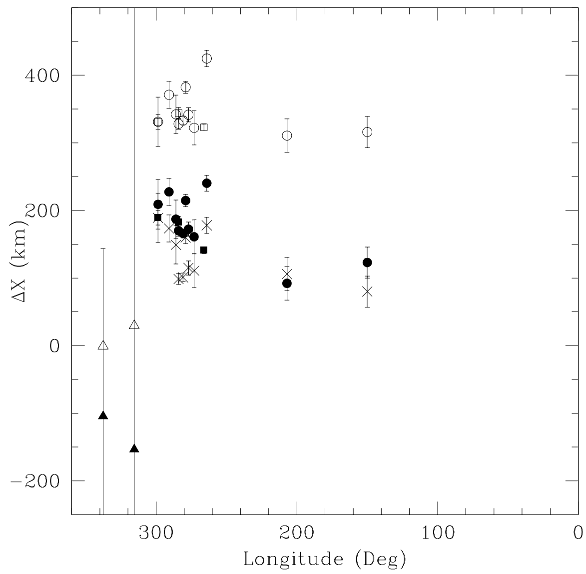

Fig. 2. Dependence of (O–C) in longitude in km for the 2E1/2O1 events versus the central meridian longitude. Open circles, filled circles and crosses denote O–C in longitude for the occultation events with respect to E3, E5 and E5+M respectively. For the eclipses of the same series, open and filled squares correspond to E3 and E5 respectively. The O–C in longitude with respect to E5 is lower compared to E3 and is lowest in the case of E5+M. The open and filled triangles represent O–C in longitude with respect to E3 and E5 of the 2E1 events of 1997. The error bars for the 2E1 events on 2 May and 12 July, 1997, are large due to poor S/N of the data (low Q values in Table 1).

O–C in longitude with respect to E3 and E5 of the 2E1 events of 1997. For these events, the E3 predictions are better than those of E5. The estimated uncertainties in the longitude ΔX and the impact parameter Y given in Tables 1 and 2 were derived from the fit to the light curves. For the two 2E1 events on 2 May and 12 July, 1997, the uncertainties in ΔX are very large because of the poor S/N or low Q values of the light curves (Table 1).

3.3. The 3O2 events of 1985

The published light curves of the 3O2 events in 1985 (Arlot et al. 1990, 1992) were re-fitted with the present model with E5+M, E5 and E3. The fitted parameters are given in Table 3. The differences in the (O–C) in longitude in the three sets are insignificant. While the lower residuals with respect to the E5 ephemerides are expected as the data set of 1985 was incorporated in its construction, lower residuals with respect to E3 are surprising. As shown in Table 1, the longitude residuals of 1997 agree better with E3 than E5, while for the 1985 series both are within the observational error in the estimate of mid-time of the light curves. The estimated uncertainties in ΔX and Y given in Table 3 were derived from the fit to the light curves.

4. Estimation of the shift of photo-center from geometric center

A comparison of ΔX and the fitted impact parameters obtained using E5+M and E5, in Table 1–3 clearly indicates that albedo variations over the surface of the satellites influence the timing and depth of the events. Unlike the shifts in the photo-center due to phase effects (Aksnes et al. 1986) that have opposite signs for occultations and eclipses, the shift in photo-center due to albedo effects have the same sign for both these types of events. The occulted/eclipsed satellite in a given mutual event series is generally confined to $\pm 20°$ of its orbital longitude. A sustained shift in the position of the photo center in all the events involving a given satellite pair, although small, will introduce a common bias in the data set. In order to look for the direction of such a bias in the case of the data sets of 1973, 1985 and 1991 involving Io and Europa, we compute the shift of the photo-center on these satellites using the expression:

$$\Delta X_{\rm Alb} = \frac{\sum_{l=-90}^{90}\sum_{b=-90}^{90} d \times I(CML+l,b) f(\mu_0,\mu,\lambda)\mu}{\sum_{l=-90}^{90}\sum_{b=-90}^{90} I(CML+l,b) f(\mu_0,\mu,\lambda)\mu},$$

where $I(CML+l,b)$ is the intensity of a surface element at the longitude of $(CML+l)$ and latitude b. The projected distance of this element on the disk of the satellite from the central meridian is d, taken positive eastwards and $f(\mu_0,\mu,\lambda)$ is the photometric function derived using Hapke's law for smooth surface at the incident and emergent angles of $\arccos(\mu_0)$ and $\arccos(\mu)$ respectively at the wavelength λ. As most observations are carried out through V filter, the green filter mosaics were used. These

Table 2. Astrometric results of the 2O1 events.

DATE Observatory	EPH.	$T_g^{\rm Fit}$ UT	ΔX km	Y km	(O–C)Y km	$\Delta\alpha\cos(\delta)$ km	$\Delta\delta$ Deg	*CML*
01 Jan. 1991	E5+M	06 27 50.5	-106 ± 25	-1765 ± 36	−41	−514	−1688	206.9
BMD	E5		-92 ± 17	-1746 ± 41	−23	−509	−1670	
	E3		-311 ± 17	-1699 ± 44	30	−495	−1626	
19 Jan. 1991	E5+M	05 33 56.2	-178 ± 12	-1523 ± 21	−9	−455	−1453	264.0
ESO	E5		-240 ± 12	-1554 ± 26	−41	−464	−1483	
	E3		-425 ± 12	-1553 ± 28	−35	−464	−1482	
22 Jan. 1991	E5+M	04 57 28.7	-80 ± 23	871 ± 59	−267	204	847	150.0
ESO	E5		-123 ± 24	905 ± 80	−233	212	879	
	E3		-316 ± 24	953 ± 83	−175	224	927	
09 Feb. 1991	E5+M	12 19 23.9	-115 ± 11	-369 ± 62	−37	−104	−354	277.0
KAK	E5		-172 ± 11	-480 ± 45	−148	−136	−461	
	E3		-342 ± 11	-482 ± 50	−141	−136	−462	
13 Feb. 1991	E5+M	01 24 21.7	-160 ± 9	-378 ± 56	−247	−106	−363	279.0
ESO	E5		-215 ± 11	-478 ± 42	−347	−134	−459	
	E3		-382 ± 11	-498 ± 56	−365	−139	−478	
16 Feb. 1991	E5+M	14 29 34.1	-101 ± 7	93 ± 140	−42	26	89	280.9
VBO	E5		-166 ± 7	130 ± 127	−5	36	125	
	E3		-333 ± 7	372 ± 56	241	103	358	
20 Feb. 1991	E5+M	03 34 5.6	-111 ± 25	332 ± 45	−30	91	319	282.6
PIC	E5		-161 ± 22	233 ± 176	−129	64	224	
	E3		-322 ± 22	176 ± 213	−181	48	169	
23 Feb. 1991	E5+M	16 39 06.1	-98 ± 8	555 ± 29	−41	154	533	284.3
VBO	E5		-170 ± 9	522 ± 31	−74	145	502	
	E3		-328 ± 9	520 ± 36	−71	144	499	
27 Feb. 1991	E5+M	05 43 37.2	-149 ± 28	885 ± 51	36	240	852	285.9
BMD	E5		-187 ± 38	891 ± 58	42	242	858	
	E3		-343 ± 36	855 ± 68	6	232	823	
09 Mar. 1991	E5+M	20 58 32.5	-173 ± 20	1508 ± 60	−22	406	1452	290.8
KAV	E5		-227 ± 20	1428 ± 67	−102	385	1375	
	E3		-371 ± 21	1392 ± 71	−134	375	1340	
27 Mar. 1991	E5+M	14 26 32.9	-189 ± 37	2506 ± 48	−22	665	2416	298.6
VBO	E5		-209 ± 39	2505 ± 50	−23	665	2415	
	E3		-331 ± 65	2493 ± 50	−29	662	2404	

mosaics of Io and Europa are shown in the top panels of Figs. 3 and 4 respectively. The gaps in the mosaics in the polar regions were filled using the average values from the neighboring regions while computing $\Delta X_{\rm Alb}$. The intensity variation along the equator are shown in the middle panels. The variation of $\Delta X_{\rm Alb}$ with CML for Io and Europa are shown in the lower panels. The range of orbital longitudes over which given sets of satellite pairs were eclipsed/occulted during 1973, 1985 and 1991 are shown as horizontal lines. The 1979 events were very sparse and hence are not included here. As shown in these figures, the albedo variations can swing the photocenter of Io by ≈90 km to the East (a positive value for $\Delta X_{\rm Alb}$) and ≈50 km to West depending on the orbital longitude of the synchronously rotating satellite. For Europa, the photo-center can shift by ≈50 km towards East and ≈30 km to the West.

The mutual event data sets yield relative astrometric positions. To assess the effect of the shift in the photocenter, a least square solution to the correction of the mean longitudes, longitude of perijove, free and forced eccentricities of the four satellites using the (O–C) in longitude (after correcting for the shift in the photo-center), of a combination of events, as carried out by Aksnes & Franklin (2001), is required. However, as the predominant participants of the mutual events are Io and Europa, and in a given mutual event season, events of any one kind are predominant (like 1E2/1O2 series in 1973 and 2E1/2O1 in 1991), we attempt in the following section to obtain a semi-quantitative explanation for 1) the delay in the 2E1/2O1 events of the 1991 series, 2) longitude residuals

Table 3. Astrometric results of the 3O2 events.

DATE Observatory	EPH.	$T_g^{\rm Fit}$ UT	ΔX km	Y km	(O–C)Y km	$\Delta\alpha\cos(\delta)$ km	$\Delta\delta$ Deg	*CML*
03 Jun. 1985	E5+M	07 07 07.3	-65 ± 7	-2266 ± 18	−77	769	−2132	53.3
ESO	E5		-40 ± 7	-2272 ± 18	−83	771	−2138	
	E3		-61 ± 7	-2247 ± 17	−54	762	−2113	
10 Jun. 1985	E5+M	10 13 37.1	-59 ± 11	-1075 ± 117	70	365	−1012	56.1
ESO	E5		-51 ± 13	-1073 ± 130	73	364	−1009	
	E3		-73 ± 13	-1071 ± 117	77	363	−1008	
16 Jul. 1985	E5+M	01 14 29.8	-17 ± 6	1657 ± 24	−14	−543	1565	70.3
BRAZIL	E5		-16 ± 6	1724 ± 24	53	−565	1629	
	E3		-31 ± 6	1723 ± 25	50	−565	1628	
23 Jul. 1985	E5+M	04 11 39.8	115 ± 5	1825 ± 15	−33	−591	1727	73.3
BRAZIL	E5		116 ± 4	1879 ± 15	21	−608	1778	
	E3		105 ± 4	1881 ± 15	19	−609	1780	
30 Jul. 1985	E5+M	07 09 42.0	41 ± 11	1735 ± 50	−236	−554	1645	76.3
BRAZIL	E5		38 ± 4	1809 ± 48	−163	−577	1714	
	E3		36 ± 4	1833 ± 48	−144	−585	1737	

Observatory Code Locations for Tables 2 and 3: BMD = Galileo Obs., Bowie, MD; BRAZIL = Laboratório. Nacional de Astrofisica, Brazil; ESO = Europian Southern Obs., Chile; KAK = Kakuda, Japan; PIC = Pic du Midi, France; VBO = Vainu Bappu Obs., India.

of the 3E2/3O2 events of the present series of 1997 and 3) the large positive (O–C) values in recent timings of eclipse (behind the planet) events of Europa (Mallama 2000).

5. Implications of cumulative and sustained longitude residuals on the constructed ephemerides

The 1E2/1O2 events in 1973 occurred when Europa was near 325° longitude. The photo-center near this longitude is ≈40 km to the East (Fig. 4). The motion of the occulted/eclipsed satellite relative to the occulting/eclipsing satellite for these events was mostly eastwards. Hence the time of light minimum would have occurred earlier than the predictions. The ephemerides E3 was constructed using a majority of collection of these 1E2/1O2 events. The shallow events will be less affected than the deeper ones. Nevertheless, a large number of these astrometric positions when incorporated into the correction to the constants would falsely identify the geometric shift of the photo-center on Europa to East as dynamical errors and interpret it as either an advancement of Europa or a delay in the motion of Io. The estimated corrections, ϵ & β, related to motions and rates (Lieske 1977) in E3 would account for an advance in Europa's longitude and/or a delay in that of Io. During the 2E1/2O1 events in 1991, Io was close to western elongation and errors in the predictions of its longitude will be of a lesser consequence, while for Europa near an orbital phase angle of 220°, the ephemerides E3, which has been forced to account for an apparently advancing Europa, will predict the events to occur earlier. Further, at $260° < CML < 320°$, the photo-center on Io is shifted to the West by ≈50 km (Fig. 2). This will further delay the events. This argument is in accordance with the observed delay in all the 2E1/2O1 events of 1991 with respect to the predictions using E3 (Mallama 1992; Vasundhara 1994).

Ephemerides E5 was constructed from a vast majority of 1E2/1O2 events in 1973, 3E2/3O2 and 1E2/1O2 events in 1985 and 2E1/2O1 events in 1991. Apart from the 3E2/3O2 events of 1985 for which $\Delta X_{\rm Alb}$ is small and distributed both to the East and West, for both the 1E2/1O2 events of 1973 and 1985, the shift $\Delta X_{\rm Alb}$ for Europa is 30−40 km to the East (Fig. 4). This trend again predicts an advancing Europa. Hence the (ϵ, β) values of E5 related to angles and rates of Europa would have been adjusted to account for its apparent advancement in longitude. Ephemerides E5 would therefore predict the 3E2/3O2 events of 1997 ahead of the actual time of occurrence. The limited data set from VBO indicates that the 3E2/3O2 events were delayed with respect to E5 by ≈65 km. Our suggestion that E5 is forced to predict the position of Europa in advance is also supported by the positive values of (O–C) of the satellite positions from the accurate CCD measurements of the eclipse timings by Mallama et al. (2000). These authors find that the motion of Io is well represented but the other satellites, in particular Europa, have (O–C) values that are larger than the observational accuracies. Apart from the shift of the photo-center along East–West, the depth of a light curve also depends on the albedo variation, in particular for Io

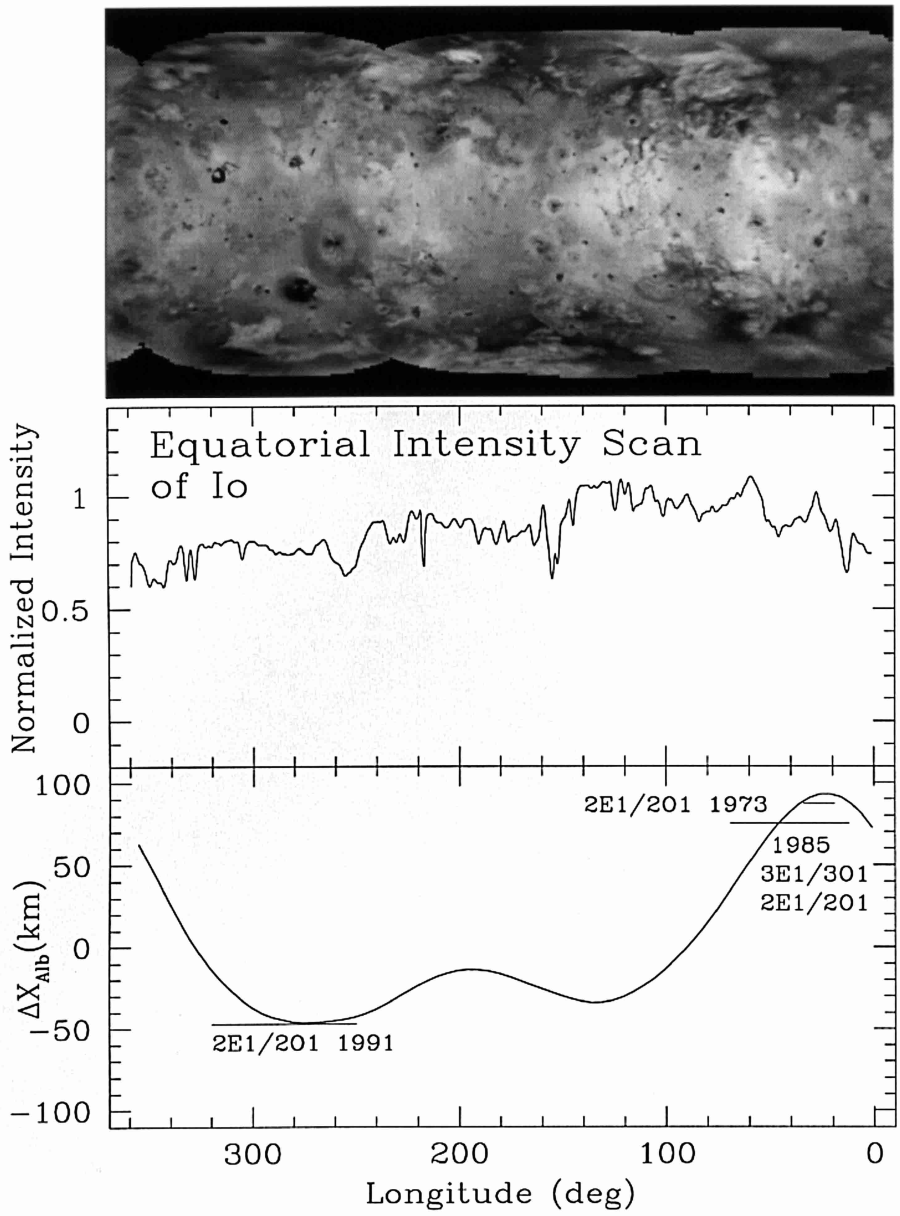

Fig. 3. The top panel shows the green filter mosaic of Io (Geissler et al. 1999) used in the present work. Variation of ΔX_{Alb} with longitude are shown in the lower panel. The intensity variation along the equator in the the mosaics are shown in the middle panel. Variation of ΔX_{Alb} with longitude are shown in the lower panel. The range of orbital longitudes over which a given set of satellite pairs were eclipsed/occulted during 1973, 1985 and 1991 are shown as horizontal lines. The longitude 0° on the satellite continuously faces Jupiter.

with dark polar regions. Hence a re-analysis of all the existing light curves of 1973–1997 taking into account the realistic albedo variations may be required for a reliable construction of the satellite ephemerides.

There are however the following limitations and possible justifications of the present argument:

1. The intensity contrast of different regions in the mosaics are assumed in this work to represent the albedo of different features. This is not strictly correct, as the photometric functions of materials in different terrains may vary. The Hapke's parameters (1984): (1) $\tilde{\omega}_0$, the single scattering albedo, (2) h, which characterizes the width of the opposition surge, (3) $S(0)$, the opposition surge amplitude, (4) g, the asymmetry factor and (5) $\tilde{\theta}$, representing the average topographic slope, vary from region to region. Only global constants of the phase functions were used in the present study. Hence the limb darkening profile may vary from region to region. The contrast between the features may change with solar phase angle of $\pm 11°$ at Jupiter's distance. That this uncertainty may be within the uncertainty in the determination of the data mid-time is seen from the unequivocal trend seen in Fig. 2 that inclusion of albedo variation reduces the O–C in longitude with

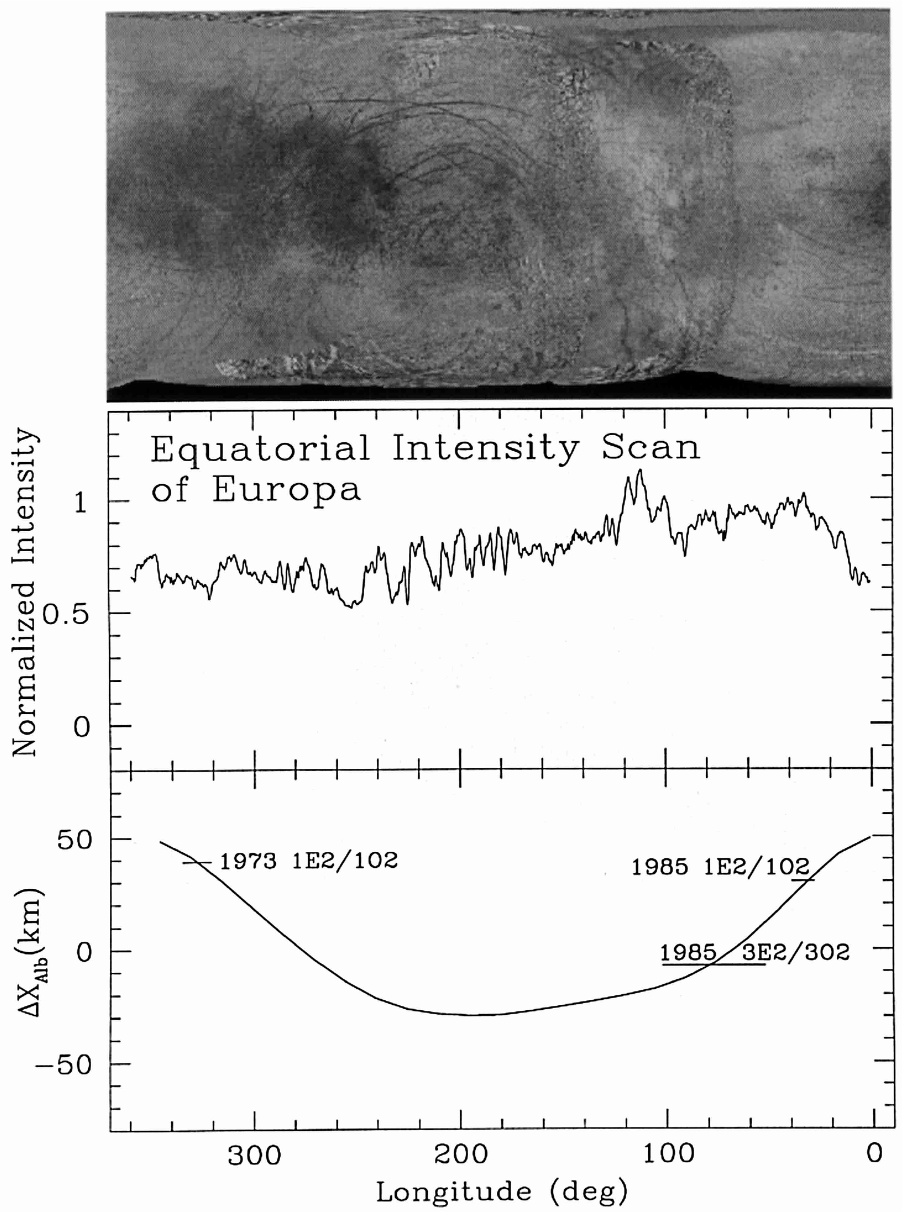

Fig. 4. Same as Fig. 3 but for Europa. The top panel shows the mosaic of Europa (Phillips et al. 1997) used in the present work.

respect to E5. The reason for this may be that the mosaics have been prepared by using low phase angle images ranging from 0°.5 to 13°.9 and corrected for the phase variations by Geissler et al. (1999).

2. At least for Io, there may be temporal variations in the contrast of the features.
3. It is not clear why the ephemerides for Io are not deteriorated in E5. One reason could be that both during 1973 and 1991, Io was near western elongation and hence (O–C) in the projected position of Io and the associated corrections to the constants of motion would be small compared to that of Europa. Alternatively, the corrections to Io introduced in E5 may account for its real retardation in longitude (thus supporting a positive value for $\dot{n}_1/n_1$).

6. Conclusions

The (O–C) in longitude and the differential coordinates of the pairs of satellites given in Table 1 for the 1997 events can be directly utilized in future studies to update the constants of motion of the satellites.

The (O–C) in longitude of the 3E2/3O2 events with respect to E5 of this series are found to be higher than those with respect to E3. This comes as a surprise as E5 was constructed by including a large number of satellite pair positions of mutual event series of 1973, 1979, 1985 and 1991, while E3 used only those of 1973 and 1979 by Lieske (1998). We suggest that the reason for this discrepancy may be at least partly due to shift of the photo-center from the geometric-center on the satellites due to albedo variations on their surfaces. In a given apparition, the mutual event series involving a given satellite pair dominate in number and occur near the same orbital longitudes within $\pm 20°$. For example, events involving Io and Europa (1E2/1O2) in 1973, Ganymede–Io and Ganymede–Europa (3E1/3O1, 1E3/3O1 & 3E2/3O2) in 1985 and Europa–Io (2E1/2O1) in 1991 were more numerous than those involving other satellite pair combinations. All the events are therefore delayed or advanced depending on the mean value of $\Delta X_{\rm Alb}$. The associated values of (O–C) in longitude may enter as dynamical errors in the newly constructed ephemerides. Hence, in order to fully exploit the potential of the mutual event data set, the astrometric information from the light curves should be extracted by taking into account the albedo variations on the satellites to remove the photometric effects.

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