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Astrometry from mutual events of Jovian satellites in 1997⋆

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Abstract. Astrometric results of observations of the mutual events of the Galilean satellites of Jupiter of the PHEMU97 campaign by the Institut de Mécanique Céleste et de Calcul des Éphémérides are presented. These astrometric positions can be directly utilized in the construction of future ephemerides. We attempt here to compare the residuals of the relative astrometric positions of satellites with respect to the E3, G5, E5 and L1 ephemerides. The model to fit the observed light curves includes the intensity variations on the surface of satellites using the mosaics constructed by the teams at the US Geological Survey from Voyager and Galileo imagery.

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

1. Introduction

The four major satellites of Jupiter occult and eclipse each other twice during the orbital period of Jupiter of about 11.6 yrs. The astrometric results of mutual events are capable of yielding accuracies of the order of 0.″03. This data set therefore has great potential in studies of secular variations in mean motion of the satellites. Of utmost importance is the evaluation of $\dot{n}_1/n_1$ (Aksnes & Franklin 2001; de Sitter 1928; Goldstein & Jacobs 1986; Goldstein & Jacobs 1995; Greenberg et al. 1986; Lieske 1998; Vasundhara et al. 1996). Addition of the mutual event data of the 1997 apparition to the earlier series of 1973, 1979, 1985 and 1991 apparitions will extend the existing time base of these data sets from 18 yrs (1973–1991) to 24 yrs. Such a data set will be helpful to re-investigate the secular variation of the mean motion of these satellites. We present here the astrometric positions derived by fitting the mutual event light curves collected during the observational campaign PHEMU97. These may be directly utilized for further upgrading the ephemerides.

2. Observations

The observations of the mutual events were made in 1997, taking opportunity of the transit of the Sun and the Earth through the equatorial plane of Jupiter. At that time, a large number of mutual occultations and eclipses occurred. These observations were carried out photometrically to obtain the light curves to determine the magnitude drop during the events. Each observation has been carefully referred to UTC, allowing astrometric use. Since the events occurred at specific dates, we organized a worldwide campaign of observations allowing to record 275 light curves for 148 events from 42 sites. All these data will be published in a catalogue and are available at the website of the Institut de Mécanique Céleste et de Calcul des Éphémérides[1]. In the past, we used these observations only to evaluate the shift of the dynamical model. However, a photometric analysis made for astrometric purposes will provide results of high interest.

3. Photometric astrometry

The light curves were fitted using the model presented in Vasundhara (1994). Hapke's photometric function with corrections for macroscopic roughness (Hapke 1984) was used to describe the limb darkening on the satellites for the occultation events. The values of the Hapke's parameters were adopted from McEwen et al. (1988) for Io and from Domingue & Verbiscer (1997) for the other satellites. For the eclipse events, the gradient of the penumbral intensity may play a more dominant role in determining the shape of the light curves than the variations in limb darkening due to surface roughness. These light curves were therefore modeled assuming a smooth photometric function (Hapke 1981) to evaluate the limb darkening.

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⋆ Tables 1 and 2 are only available in electronic form at `http://www.edpsciences.org`

[1] `ftp://ftp.bdl.fr/pub/NSDC/jupiter/raw_data/phenomena/mutual/1997`

The intensity variations on the surface of the satellites were taken into account by using the mosaics of the satellites constructed using Voyager and Galileo imagery made by various groups. The mosaics of Io at 5 km/pixel through green and near infrared filters (NIR) were constructed by Geissler et al. (1999) using images obtained by Galileo's Solid State Imaging System (SSI) at lowest phase angles ranging from $0\overset{\circ}{.}5$ to $13\overset{\circ}{.}9$. A simple Lunar-Lambert phase dependent photometric function from McEwen (1991) was used to account for limb darkening. The medium phase angle images ($4\overset{\circ}{.}1$–$4\overset{\circ}{.}9$) were directly mosaicked while the low phase angle ($0\overset{\circ}{.}5$) and higher phase angle ($13\overset{\circ}{.}9$) images were corrected to account for variation with phase angle by these authors. For Europa, the mosaic constructed by the United States Geological Survey (USGS) team using Voyager 1 & 2 and Galileo images was used. Their image processing included corrections for limb darkening using modified Hapke function and normalizing brightness variations due to differences in Sun angle and viewing geometry (Phillips et al. 1997). Considering the lower contrast of features on Europa, a lower resolution of 8 km/pixel was considered adequate. The mosaics of Ganymede (at 2 km/pixel) and Callisto (at 4 km/pixel) constructed by the USGS team were down loaded from the website of the United States Geological Survey, Astrogeology Program, Flagstaff, Arizona[2]. The construction of the mosaics as described by Becker et al. (1999) involved radiometric calibration, photometric normalization by applying the Lunar-Lambert values that were derived from empirical fits to Hapke's functions (McEwen 1991). All these mosaics are thus well calibrated and ideally suited for modeling low phase angle ground based observations as in the present case.

The impact parameter and the time difference between the observation and the prediction were derived as free parameters by fitting the observed light curves to the model using "Grid Search" technique (Bevington 1969). In case of occultations and also for eclipse events close to opposition the two satellites are very close in the aperture for photometry using photoelectric photometry as well as aperture photometry of CCD data. Ideally, the contribution of the two satellites should be measured just before/after the event. This was not carried out in the majority of the cases. Hence the contribution "r" of the eclipsing/occulting satellite to the total flux

$$r = IS_1/(IS_1 + IS_2) \quad (1)$$

was determined as a third parameter, where IS_1 and IS_2 are the sky subtracted flux measurements of the eclipsing/occulting satellite and eclipsed/occulted satellites respectively.The fitted parameter "r" (Eq. (1)) should in principle absorb the uncertainty in the sky measurements. The solutions converged within 6–8 iterations for the good quality light curves. The impact parameter "IP" and "r" both influence the depth of the light curve. The former also influences the duration of the light curve. As the relative velocity between the two satellites for occultations and the velocity of the eclipsed satellite relative to the shadow center for eclipses can be determined accurately from theory, "IP" and hence "r" are determined without ambiguity except in case of very noisy light curves. As the model takes into account the shift in the light center on the satellite from the geometric center due to intensity variations 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 as compared to predictions using the E3 (Lieske 1987). The time

$$T_{\rm g}^{\rm Fit} = T_{\rm g}^{\rm Pred} - \Delta X/v \quad (2)$$

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, where v is the velocity of the occulted (eclipsed) satellite relative to the occulting (eclipsing) satellite. The fitted ΔX in the above equation represents the shift of the computed curve along the time axis required to fit the observations. The fitted astrometric results for different sets of events are given in Table 1. The date of the event is given in Col. 1. Following the normal practice of designating the events, the code 1E2 indicates that Io eclipses Europa. Similarly, 1O2 denotes the occultation of Europa by Io. The derived value of $T_{\rm g}^{\rm Fit}$, fitted impact parameter, IP and ΔX are given in Cols. 2–4 respectively. The (O–C) in the impact parameter is given in Col. 5. The differential sky plane coordinates $\Delta\alpha\cos\delta$ and $\Delta\delta$ of J2000 epoch, in the sense (S2–S1) in arcsec are given in Cols. 6 and 7 respectively. The orbital longitudes $\phi1$ and $\phi2$ of the occulting/eclipsing and occulted/eclipsed satellites, geocentric for occultations and heliocentric for eclipses are given in Cols. 8 and 9 respectively. The site of observations are given in the last column.

4. Comparison with theory

The (O–C) in differential coordinates $\Delta\alpha\cos\delta$ and $\Delta\delta$ of the pairs of satellites are plotted in Figs. 1 and 2 respectively with respect to E3, G5, E5 and L1 (see references below). The symbols used for the different events are as follows: 1E2: open triangles, 1O3/1E3: stars, 1E4: open stars. 2E1: filled triangles, 2O3: open circles, 3O1/3E1: crosses, 3O2/3E2: filled circles, 3O4/3E4: open hexagons, 4O1/4E1: filled hexagons, 4O2/4E2: open squares and 4O3/4E3: filled squares. Due to differences in the data sets that went into generation of these ephemerides, it is of interest to look for existence of general trends if any, in the residuals. For instance, Lieske progressively updated Sampson's (1921) theory starting from E1 (Lieske 1977) using the eclipse data of 1878–1903 to generate E2 (Lieske 1980) by adding visual eclipses between 1903 and 1972, photographic data between 1967 and 1978, and mutual events of 1973. The E3 (Lieske 1987) ephemerides was derived by further mutual event pairs from 1979, 183 pairs of data from Voyager optical navigation images and 15 711 classical eclipses from 1652–1983. Arlot (1982) used 8856 individual photographic observations between 1891 to 1978 to derive the G5 ephemeris. The E5 sets of constants were derived by Lieske by adding to the data set the mutual event astrometric positions of 1985 and 1991, recent photographic observations from Pascu (1994) covering 1980–1991 and Jovian eclipse timings.

[2] http://astrogeology.usgs.gov/Projects/JupiterSatellites

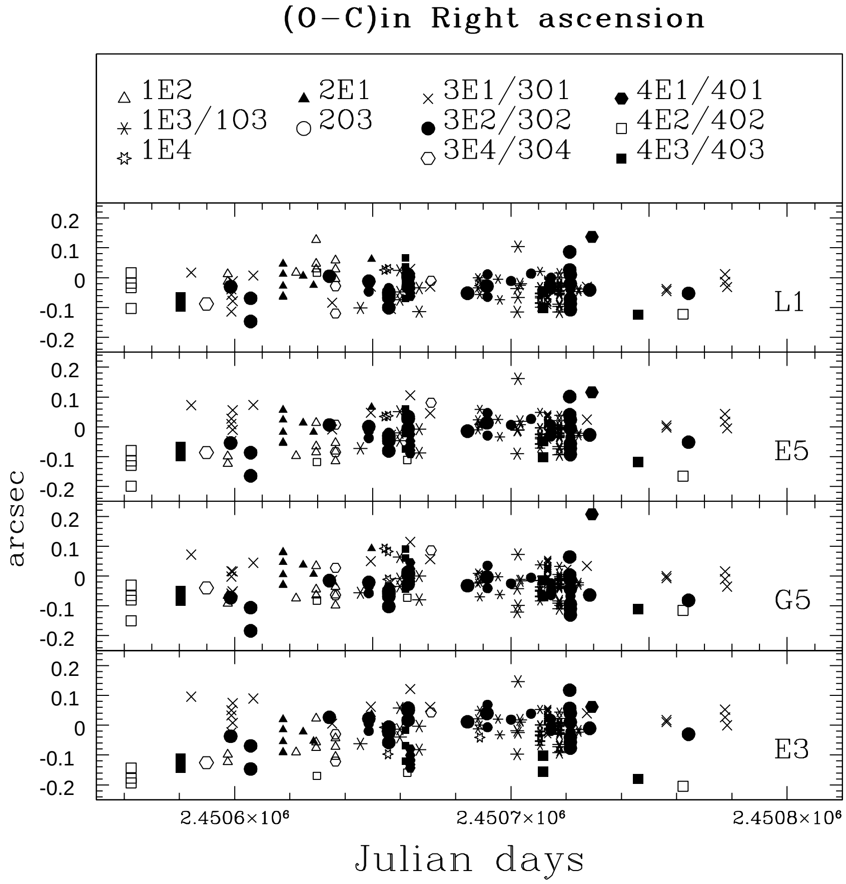

Fig. 1. O–C in (Δ RA cos(δ)) with respect to E3, G5, E5 and L1 respectively. Smaller points indicate eclipses and the larger ones occultations.

Lainey (2002) used all the observations used in the construction of G5, 200 photographic positions by Pascu (1994) made during the years 1986 to 1990, astrometric positions of the 1985 and 1991 mutual event series, and 200 CCD observations from Flagstaff (Stone & Harris 2000; Stone 2001) to construct the first version of the ephemerides L1. Thus, a comparison of E3 with E5 will help to investigate the influence of mutual events in the construction of new ephemerides and the ability of the dynamical model to fit all the data. The ephemeride G5 was generated using only photographic data, hence its comparison with E3 and G5 will be interesting to see how the eclipse timings and the mutual event data have influenced E3 and E5.

5. Interpretations and conclusions

Unlike the mutual events of the 1991 series which were predominant in the 2O1/2E1 events, the present series provided a good opportunity to record events between different pairs of satellites. The longitude of the satellites at the time of the events are shown in Fig. 3. The same symbols are used for different events as used in Figs. 1 and 2. The mean and rms of the residuals in the relative right ascensions and declinations are given in Table 2. The rms of the residuals with respect to the four ephemerides are very nearly the same for different pairs of satellites . The light curves were also fitted without considering the intensity variations due to surface features (model-WOIV). The rms residuals of the fits using this model are marginally larger compared to the corresponding values derived using the model-WIV by ~0.″01 i.e. ~35 km. This is much lower than the rms of the residuals which are in the range 0.″05–0.″07. It may be noted that the light curves were obtained by a diverse section of observers and instruments, errors in the observed depths of the light curves are transmitted in the determination of the impact parameters. Although as mentioned in Sect. 3, the parameter "*r*" was derived as a free parameter to take into account these uncertainties, fits using the model-WIV will help in better constraining this parameter and the impact parameter compared to the fits using the model-WOIV because the former takes into advantage the subtle asymmetries in the light curves due to surface features. The full potential of this model can best be realized with high quality light curves, as the genuine asymmetries may otherwise be lost in noise.

Interesting trends in the residuals of the relative right ascensions between different pairs of satellites compared to the ephemerides E3, G5, E5 and L1 (Sect. 4) are noticed. The events involving J4 are delayed by 0.″1048 compared to E3. Lowest residuals are obtained with respect to G5 both in right ascension and declination. Thus J4 related events appear to be best represented by G5 and closely followed by L1.

As shown in Figs. 1 and 2, O–C in RA and Dec with respect to these four ephemerides for the occultation and eclipse events between Io and Ganymede (1O3/1E3 and 3O1/3E1) do not differ significantly. On the other hand, significant differences are

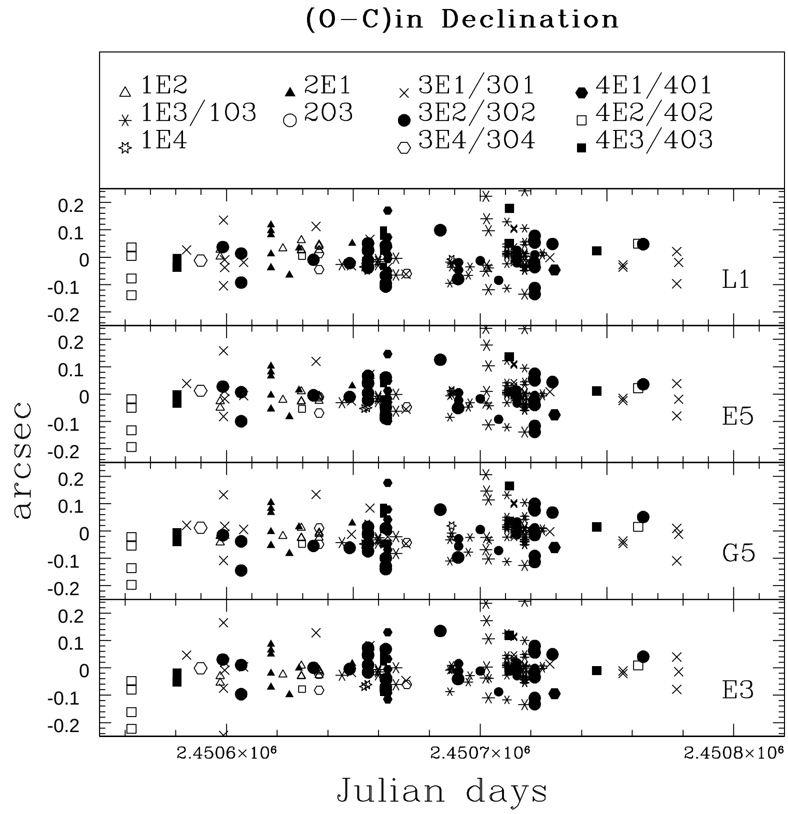

Fig. 2. O–C in $\Delta\delta$ with respect to E3, G5, E5 and L1. Smaller points indicate eclipses and the larger ones occultations.

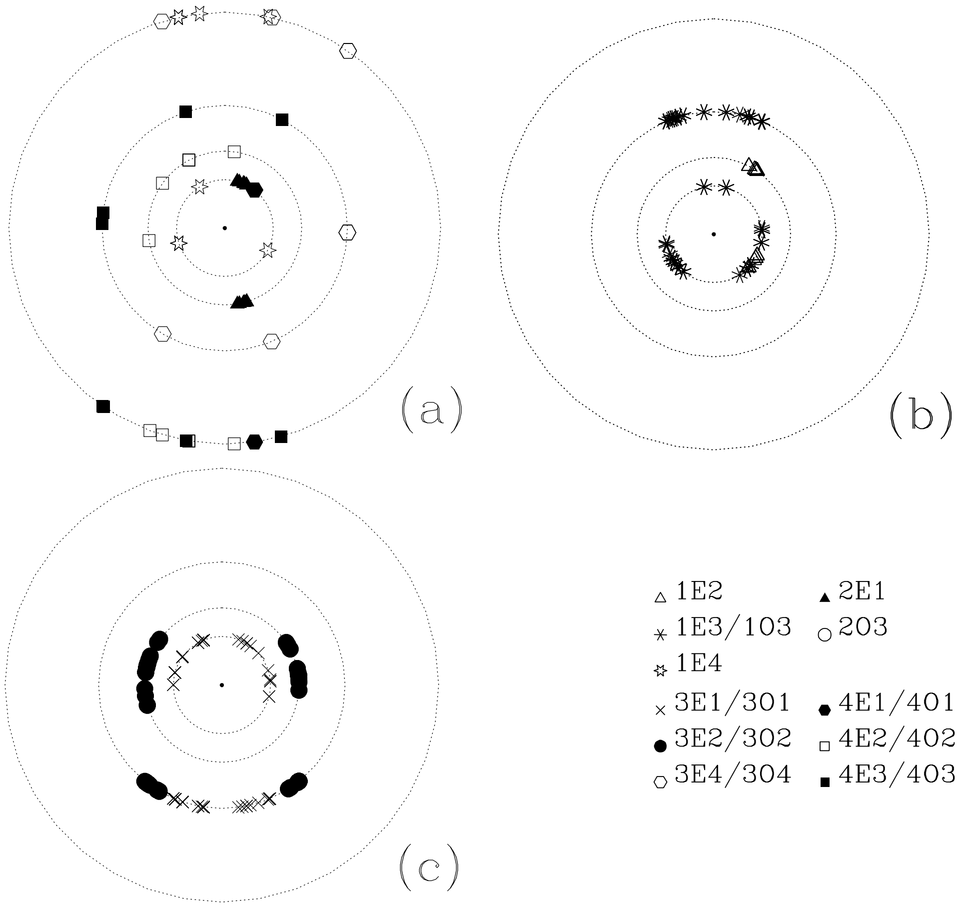

Fig. 3. Satellite positions at the time of events involving different pairs of satellites during the mutual event series of 1997.

noticed for the eclipse events between Io and Europa (1E2 and 2E1) These are more for the former type of events, which occurred when Io was closer to western elongation and hence the timings of the events are more susceptible to the constants of Europa (Fig. 3).

In any given mutual event series, as the inter-combination of events is limited, inclusion of data sets of several apparitions will help to simultaneously improve the constants of motions of these satellites. The astrometric positions presented in the present work will therefore substantially increase the mutual event data set. Improvements in the residuals by including the intensity variations on the surface of the satellites in the fit to the light curves has been demonstrated in the present investigation. A re-analysis of all the mutual event light curves of the previous series using this model will help in removing systematic shifts in the relative right ascensions of a given satellite pair, which otherwise might be misinterpreted as real longitude residuals.

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Online Material

Table 1. Astrometric results of the 1997 events.

DATE	T_g^{Fit}	ΔX	IP^{Fit}	(O−C)IP	$\Delta\alpha\cos(\delta)$	$\Delta\delta$	$\phi 1$	$\phi 2$	PLACE
	UT	km	km	km	arcsec	arcsec	Deg	Deg	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1E2 events									
29 May 1997	01 10 00.8	−404.4	−650	−81.1	0.0539	−0.1679	226.4	332.7	Boskoop
29 May 1997	01 10 58.1	−1787.0	203	772.2	−0.0176	0.0521	226.4	332.7	Lumezzane*
29 May 1997	01 10 03.2	−464.4	−537	33.3	0.0436	−0.1390	226.4	332.7	Munich
22 June 1997	21 5 47.4	−343.8	1649	17.0	−0.1439	0.4242	237.1	327.9	Alma−Ata
29 June 1997	23 23 30.1	−228.0	2172	−42.0	−0.1928	0.5578	240.4	326.7	Bucharest(S)
29 June 1997	23 23 33.7	−298.7	2200	−13.7	−0.1937	0.5655	240.4	326.7	Bucharest(V)
29 June 1997	23 23 14.5	84.2	2210	−3.4	−0.1936	0.5685	240.4	326.7	Stuttgart
07 July 1997	01 42 32.9	−400.1	2797	27.6	−0.2486	0.7186	243.8	325.5	Bordeau
07 July 1997	01 42 20.5	−165.9	2772	2.4	−0.2464	0.7121	243.8	325.5	Lisbon
07 July 1997	01 42 25.6	−261.7	2825	55.3	−0.2511	0.7257	243.8	325.5	San Fernando
1O3 events									
15 July 1997	18 58 19.5	−209.6	2277	−24.2	−0.2645	0.7110	212.5	347.7	Alma−Ata
29 July 1997	23 49 33.5	131.3	1819	−142.3	−0.2108	0.5798	224.1	344.0	Boskoop
29 July 1997	23 49 44.3	−118.7	1971	11.1	−0.2284	0.6281	224.1	344.0	Bucharest (V)
29 July 1997	23 49 41.6	−55.0	1923	−37.8	−0.2228	0.6130	224.1	344.0	Comthurey
29 July 1997	23 50 20.6	−945.1	1802	−158.8	−0.2092	0.5744	224.1	344.0	Reux
06 Aug. 1997	02 17 55.7	−640.6	1517	−89.7	−0.1742	0.4860	230.2	342.2	Grasse (B)
06 Aug. 1997	02 17 51.7	−554.5	1430	−175.9	−0.1643	0.4584	230.2	342.2	Grasse (V)
06 Aug. 1997	02 17 29.0	−68.1	1428	−179.0	−0.1640	0.4575	230.2	342.2	Munich
06 Aug. 1997	02 17 36.7	−229.7	1678	72.7	−0.1926	0.5380	230.2	342.2	Teide (T150, K)
10 Sep. 1997	16 17 37.2	−95.6	−868	−93.9	0.0912	−0.2704	274.8	336.8	Alma−Ata
10 Sep. 1997	16 17 31.5	−54.1	−8	769.6	0.0008	−0.0024	274.8	336.8	Funaho
10 Sep. 1997	16 17 33.9	−74.5	−848	−70.4	0.0875	−0.2647	274.8	336.8	Okayama
11 Sep. 1997	00 31 38.4	−66.9	−2002	31.3	0.2140	−0.6217	345.1	354.2	Bordeaux
11 Sep. 1997	00 33 28.7	592.1	−1685	349.1	0.1801	−0.5234	345.1	354.2	Catania
11 Sep. 1997	14 08 09.0	152.1	−2416	288.4	0.2540	−0.7515	101.1	22.9	Funaho
11 Sep. 1997	14 09 31.5	−945.8	−2738	−33.0	0.2873	−0.8517	101.1	22.9	Okayama
25 Sep. 1997	19 54 23.8	44.2	−2564	792.5	0.2562	−0.7716	119.4	20.2	Boskoop
25 Sep. 1997	19 54 37.7	−214.4	−3273	84.7	0.3269	−0.9847	119.4	20.2	Meudon
25 Sep. 1997	19 54 42.6	−306.4	−3359	−1.7	0.3356	−1.0107	119.4	20.2	Munich
25 Sep. 1997	19 54 29.8	−66.7	−3782	−424.6	0.3778	−1.1379	119.4	20.2	Paris
02 Oct. 1997	22 40 36.6	−451.8	−2615	1019.7	0.2548	−0.7714	127.3	18.4	Bordeaux
1E3 events									
27 Aug. 1997	11 29 33.1	−32.1	−1360	−324.0	0.1262	−0.3486	260.1	337.1	Funaho
27 Aug. 1997	11 29 34.5	−51.2	−1049	−14.1	0.0974	−0.2690	260.1	337.1	Okayama
28 Aug. 1997	00 36 18.0	164.5	−2752	−76.5	0.2609	−0.7030	11.7	4.6	Catania
28 Aug. 1997	00 35 53.2	10.8	−2641	34.5	0.2505	−0.6746	11.7	4.6	Teide (T150, K)
03 Sep. 1997	15 26 14.0	4.7	−827	−203.8	0.0778	−0.2118	277.3	336.9	Alma−Ata
04 Sep. 1997	13 13 27.1	−147.4	−2096	−53.2	0.1998	−0.5358	102.8	22.7	Okayama
11 Sep. 1997	16 30 22.5	−13.2	−1324	−142.6	0.1263	−0.3387	114.4	21.1	Vainu Bappu Obs.

Table 1. continued.

DATE	T_g^{Fit}	ΔX	IP^{Fit}	(O−C)IP	$\Delta\alpha\cos(\delta)$	$\Delta\delta$	$\phi1$	$\phi2$	PLACE
	UT	km	km	km	arcsec	arcsec	Deg	Deg	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
			1E3 events (continued)						
18 Sep. 1997	19 34 51.4	22.0	290	547.7	−0.0507	0.0609	124.1	19.2	Bucharest
18 Sep. 1997	19 34 55.6	−55.6	−154	96.3	0.0159	−0.0391	124.1	19.2	Boskoop
18 Sep. 1997	19 34 53.4	−10.4	−350	−96.0	0.0797	−0.0530	124.1	19.2	Bordeaux
18 Sep. 1997	19 34 58.5	−114.6	−172	75.6	0.0170	−0.0439	124.1	19.2	Lisbon
18 Sep. 1997	19 34 57.9	−104.3	−311	−63.7	0.0297	−0.0797	124.1	19.2	Grasse (B)
18 Sep. 1997	19 35 1.6	−177.3	−172	75.6	0.0164	−0.0440	124.1	19.2	Grasse (V)
18 Sep. 1997	19 34 59.1	−129.9	−18	229.0	0.0016	−0.0047	124.1	19.2	Grasse (R)
18 Sep. 1997	19 34 57.4	−94.8	−163	85.6	0.0156	−0.0418	124.1	19.2	Reux
18 Sep. 1997	19 35 00.6	−156.2	−645	−397.2	0.0641	−0.1640	124.1	19.2	Naucshny
18 Sep. 1997	19 34 54.8	−38.3	−155	98.4	0.0355	−0.0231	124.1	19.2	Torino
25 Sep. 1997	22 32 42.7	−150.9	639	−113.0	−0.0598	0.1641	132.8	16.9	Bordeaux
25 Sep. 1997	22 32 34.5	27.5	769	18.5	−0.0768	0.1956	132.8	16.9	Reux
25 Sep. 1997	22 32 41.5	−126.3	622	−128.2	−0.0601	0.1589	132.8	16.9	Ukkel
25 Sep. 1997	22 32 37.9	−45.7	916	166.0	−0.0881	0.2343	132.8	16.9	Boskoop
25 Sep. 1997	22 32 28.7	157.2	1076	326.6	−0.1046	0.2749	132.8	16.9	Wilp−Achterhoek
25 Sep. 1997	22 32 37.8	−44.3	957	207.0	−0.0931	0.2443	132.8	16.9	Heisingen
25 Sep. 1997	22 32 34.0	40.2	766	16.2	−0.0752	0.1953	132.8	16.9	Grasse (B)
25 Sep. 1997	22 32 31.7	92.1	546	−203.8	−0.0531	0.1394	132.8	16.9	Grasse (V)
25 Sep. 1997	22 32 42.9	−156.6	592	−157.5	−0.0575	0.1513	132.8	16.9	Grasse (R)
25 Sep. 1997	22 32 41.0	−116.1	729	−20.5	−0.0715	0.1860	132.8	16.9	Munich
25 Sep. 1997	22 32 36.7	−19.2	750	−0.8	−0.0734	0.1914	132.8	16.9	Obs. Haute Provence
25 Sep. 1997	22 32 38.1	−51.7	633	−117.2	−0.0618	0.1614	132.8	16.9	Paris
25 Sep. 1997	22 32 51.6	−348.9	738	−11.9	−0.0719	0.1884	132.8	16.9	Pic−du−Midi
25 Sep. 1997	22 32 39.0	−69.9	563	−188.0	−0.0545	0.1437	132.8	16.9	Prague
25 Sep. 1997	22 32 36.9	−30.1	787	30.7	−0.0822	0.1986	132.8	16.9	Stuttgart
03 Oct. 1997	01 25 24.1	−52.6	1792	8.3	−0.1769	0.4568	140.8	14.5	Bowie
03 Oct. 1997	01 25 25.0	−74.1	1833	48.9	−0.1800	0.4675	140.8	14.5	New−York
				1E4 events					
24 July 1997	18 21 10.1	−105.1	−64	−292.2	0.0045	−0.0168	242.8	348.4	Alma−Ata
25 July 1997	20 51 33.2	−31.2	−2123	−38.7	0.1896	−0.5458	108.2	12.4	Alma−Ata
25 July 1997	20 52 1.7	−413.3	−2175	−90.3	0.1942	−0.5590	108.2	12.4	Naucshny
28 Aug. 1997	02 52 37.8	−147.8	3245	27.3	−0.3081	0.8290	31.2	6.7	Teide (T150, K)
				2E1 events					
18 June 1997	01 04 44.8	−264.6	18	286.7	−0.0016	0.0046	196.4	333.4	Bordeaux
18 June 1997	01 04 43.8	−238.9	67	330.2	−0.0056	0.0174	196.4	333.3	Catania
18 June 1997	01 04 34.1	41.9	−356	−91.3	0.0315	−0.0913	196.4	333.4	Grasse (B)
18 June 1997	01 04 40.3	−134.8	−491	−227.1	0.0428	−0.1263	196.4	333.4	Grasse (V)
18 June 1997	01 04 29.9	162.2	16	279.8	−0.0013	0.0042	196.4	333.3	Grasse (R)
18 June 1997	01 04 45.6	−285.9	−447	−181.3	0.0416	−0.1141	196.5	333.4	Prague
25 June 1997	03 17 07.3	−192.3	−5	−321.9	0.0005	−0.0013	194.9	335.9	Lisbon
28 June 1997	16 23 16.5	−176.0	670	50.1	−0.0623	0.1713	194.1	337.3	Ellinbank
19 July 1997	22 59 41.4	145.5	2492	5.8	−0.2223	0.6409	189.4	345.1	Bordeaux
				2O3 events					
13 May 1997	02 23 50.7	−428.6	1042	119.7	−0.1033	0.2709	143.7	22.0	Ragusa
16 Oct. 1997	17 36 47.4	−572.4	1595	−113.5	−0.1485	0.4516	192.8	352.0	Torino

Table 1. continued.

DATE	T_g^{Fit}	ΔX	IP^{Fit}	(O−C)IP	$\Delta\alpha\cos(\delta)$	$\Delta\delta$	$\phi1$	$\phi2$	PLACE
	UT	km	km	km	arcsec	arcsec	Deg	Deg	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
				3O1 events					
15 May 1997	20 59 54.5	355.9	−2520	37.0	0.2509	−0.6616	161.3	54.9	Vainu Bappu Obs.
30 May 1997	03 05 19.2	104.2	−164	550.2	0.0171	−0.0451	157.8	75.0	Bordeaux
30 May 1997	03 05 26.7	−5.3	−995	−280.7	0.1040	−0.2734	157.8	75.0	Paris
30 May 1997	03 05 36.5	−149.4	−1563	−848.3	0.1614	−0.4302	157.8	75.0	Torino
31 May 1997	00 30 37.2	38.7	−2401	52.6	0.2552	−0.6603	202.6	256.5	Munich
31 May 1997	00 30 08.0	214.1	−2572	−118.3	0.2733	−0.7073	202.6	256.5	Stuttgart
05 July 1997	16 00 58.9	144.9	1170	351.7	−0.1345	0.3578	197.2	311.1	Ellinbank
07 June 1997	04 32 33.4	227.9	−1749	−86.3	0.2044	−0.4864	203.2	275.0	Teide
19 July 1997	20 59 16.8	152.5	1112	−121.1	−0.1304	0.3499	193.4	323.6	Alma−Ata
26 July 1997	23 23 19.2	47.4	1431	226.3	−0.1681	0.4544	191.5	329.3	San Fernando
03 Aug. 1997	01 44 51.9	310.9	826	−196.5	−0.0962	0.2643	189.6	334.7	Boskoop
10 Aug. 1997	04 05 28.5	124.9	508	−198.1	−0.0598	0.1625	187.7	340.0	Teide (T150, K)
03 Nov. 1997	10 27 30.7	44.6	−2276	−60.9	0.2043	−0.6078	161.5	54.0	Funaho
03 Nov. 1997	10 27 32.3	11.1	−2298	−83.1	0.2063	−0.6138	161.5	54.0	Okayama
05 Oct. 1997	23 25 59.6	138.0	−2643	15.2	0.2553	−0.7739	170.8	24.3	ESO−T220
24 Nov. 1997	20 32 09.0	110.1	−1400	−347.6	0.1157	−0.3511	156.8	89.6	Teide T80
24 Nov. 1997	20 32 06.1	140.6	−946	106.3	0.0826	−0.2356	156.8	89.7	Teide (T150, K)
25 Nov. 1997	18 39 29.7	−19.4	−2940	−52.5	0.2575	−0.7301	202.9	276.6	Ukkel
				3E1 events					
21 Sep. 1997	20 31 10.0	16.9	1624	64.0	−0.1566	0.4156	171.5	22.2	Boskoop
21 Sep. 1997	20 31 05.5	132.6	1647	78.0	−0.1610	0.4207	171.5	22.2	Bucharest (S)
21 Sep. 1997	20 31 06.5	111.0	1579	19.0	−0.1527	0.4039	171.5	22.2	Bucharest (V)
21 Sep. 1997	20 31 06.5	114.8	1573	−38.3	−0.1456	0.4047	171.5	22.2	Caceres
21 Sep. 1997	20 31 07.2	90.6	1534	−27.9	−0.1511	0.3912	171.5	22.2	Chateaugiron
21 Sep. 1997	20 31 13.2	−70.9	1698	138.1	−0.1642	0.4343	171.5	22.2	Lisbon
21 Sep. 1997	20 30 59.3	302.2	1880	319.5	−0.1818	0.4807	171.5	22.2	Grasse (V)
21 Sep. 1997	20 31 01.2	253.5	1648	88.1	−0.1593	0.4216	171.5	22.2	Grasse (R)
21 Sep. 1997	20 31 03.9	178.8	1515	−45.0	−0.1460	0.3877	171.5	22.2	Lisbon
21 Sep. 1997	20 31 05.3	140.9	1586	26.2	−0.1535	0.4057	171.5	22.2	Meudon
21 Sep. 1997	20 31 11.0	−10.1	1565	4.5	−0.1513	0.4002	171.5	22.2	Munich
21 Sep. 1997	20 31 07.4	84.7	1483	−76.8	−0.1442	0.3791	171.5	22.2	Oostduinkerke
21 Sep. 1997	20 31 06.2	118.2	1945	384.6	−0.1881	0.4974	171.5	22.2	Pic−du−Midi
21 Sep. 1997	20 31 12.9	−62.1	1604	43.8	−0.1552	0.4102	171.5	22.2	Prague
21 Sep. 1997	20 31 08.4	59.4	1544	−15.7	−0.1488	0.3952	171.5	22.2	Reux
21 Sep. 1997	20 34 12.3	−4881.4	451	−1110.6	−0.0436	0.1153	171.5	22.2	Stuttgart*
21 Sep. 1997	20 31 08.0	70.2	1985	425.3	−0.1919	0.5078	171.5	22.2	Ukkel
21 Sep. 1997	20 31 05.8	125.2	1509	−53.4	−0.1496	0.3847	171.5	22.2	Wilp−Achterhoek
21 Sep. 1997	20 31 08.0	67.7	1522	−43.1	−0.1489	0.3885	171.5	22.2	Zaragoza
28 Sep. 1997	23 18 07.3	−1075.5	2115	−294.6	−0.2061	0.5407	168.9	29.4	Catania*
28 Sep. 1997	23 17 22.1	92.5	2373	−35.7	−0.2309	0.6067	168.9	29.5	Pic−du−midi
18 Nov. 1997	19 18 35.7	−711.8	5078	25.8	−0.5306	1.2882	201.9	287.7	Catania*

Table 1. continued.

DATE	T_g^{Fit}	ΔX	IP^{Fit}	(O−C)IP	$\Delta\alpha\cos(\delta)$	$\Delta\delta$	$\phi1$	$\phi2$	PLACE
	UT	km	km	km	arcsec	arcsec	Deg	Deg	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
				3O2 events					
29 May 1997	23 07 13.8	−104.1	1562	135.8	−0.1602	0.4301	149.5	53.6	Vainu Bappu Obs.
06 June 1997	02 19 18.3	−350.4	1708	−228.6	−0.1801	0.4810	148.3	56.5	Bordeaux
06 June 1997	02 19 20.8	−358.4	2132	161.4	−0.2466	0.5916	148.3	56.5	Teide
18 July 1997	20 47 57.6	52.3	1823	−42.4	−0.2060	0.5750	142.8	74.0	Alma−Ata
18 July 1997	20 48 47.1	−559.3	1775	−91.3	−0.2003	0.5599	142.8	74.0	Torino
04 July 1997	14 43 31.2	72.8	2403	−35.3	−0.2697	0.7352	144.3	68.0	Okayama
25 July 1997	23 50 08.7	24.0	1541	125.3	−0.1733	0.4915	142.2	77.2	Boskoop
25 July 1997	23 50 08.9	24.7	1627	212.1	−0.1832	0.5190	142.2	77.2	Losbon
25 July 1997	23 50 26.4	−179.3	1420	4.6	−0.1599	0.4528	142.2	77.2	Lumezzane
25 July 1997	23 50 08.7	21.4	1552	138.1	−0.1749	0.4949	142.2	77.2	Naucshny
25 July 1997	23 50 16.3	−60.8	1462	46.9	−0.1647	0.4662	142.2	77.2	San Fernanho
02 Aug. 1997	02 53 10.6	90.9	613	−256.7	−0.0683	0.1971	141.7	80.5	Catania
02 Aug. 1997	02 53 13.8	57.4	590	−281.0	−0.0656	0.1897	141.7	80.5	Grasse B
02 Aug. 1997	02 53 09.6	102.7	701	−170.4	−0.0781	0.2252	141.7	80.5	Gragge (V)
02 Aug. 1997	02 53 09.0	110.9	1039	168.6	−0.1159	0.3340	141.7	80.5	Teide (T150, K)
23 Aug. 1997	12 29 47.5	152.6	−852	365.8	0.0897	−0.2743	141.3	92.6	Okayama
30 Aug. 1997	16 03 31.4	73.7	−2233	−153.3	0.2279	−0.7144	141.8	98.1	Alma−Ata
29 Sep. 1997	18 42 07.3	240.7	−1608	126.2	0.1618	−0.4779	218.7	274.5	Bucharest (S)
29 Sep. 1997	18 42 37.3	−42.2	−1452	281.7	0.1484	−0.4309	218.7	274.6	Bucharest (V)
29 Sep. 1997	18 42 32.8	2.8	−2109	−375.6	0.2151	−0.6258	218.7	274.6	Catania
29 Sep. 1997	18 41 58.8	324.7	−1909	−176.2	0.1972	−0.5659	218.7	274.6	Chateaugiron
29 Sep. 1997	18 42 16.4	156.3	25	1758.5	−0.0025	0.0075	218.7	274.5	Meudon
29 Sep. 1997	18 42 51.7	−175.7	−1487	246.5	0.1517	−0.4413	218.7	274.6	Obs. Haute Provence
29 Sep. 1997	18 43 06.0	−310.6	−2075	−342.2	0.2117	−0.6160	218.7	274.6	Pic−du−Midi
29 Sep. 1997	18 42 33.8	−6.9	−1848	−115.3	0.1885	−0.5486	218.7	274.5	Ukkel
06 Oct. 1997	22 12 40.8	21.6	−1370	161.8	0.1348	−0.3988	218.4	279.0	Teide T80
11 Nov. 1997	15 38 23.8	−54.6	643	173.5	−0.0579	0.1667	213.9	297.8	Vainu Bappu Obs.
				3E2 events					
18 July 1997	18 56 55.9	−79.0	−3395	−8.4	0.2954	−0.8761	143.5	70.9	Alma−Ata
18 July 1997	18 56 49.2	7.8	−3417	−30.0	0.2973	−0.8816	143.5	70.9	Vainu Bappu Obs.
25 July 1997	22 31 58.6	−69.1	−3097	6.3	0.2711	−0.7989	142.6	74.9	Alma−Ata
25 July 1997	22 31 53.6	−10.1	−3072	31.9	0.2696	−0.7921	142.6	74.9	Bucharest (V)
25 July 1997	22 31 56.0	−38.2	−2914	189.7	0.2551	−0.7516	142.6	74.9	Catania
25 July 1997	22 31 55.5	−31.5	−3178	−74.9	0.2781	−0.8199	142.6	74.9	Lisbon
30 Aug. 1997	18 44 49.9	255.5	−3810	−24.3	0.3341	−0.9851	143.0	105.0	Alma−Ata
30 Aug. 1997	18 45 49.0	−38.5	−3816	−29.9	0.3347	−0.9865	143.0	105.0	Obs. Haute Provence
08 Sep. 1997	11 04 13.0	47.8	−468	−64.1	0.0466	−0.1190	218.7	266.2	Funaho
08 Sep. 1997	11 04 15.6	28.8	386	790.2	−0.0385	0.0983	218.7	266.2	Okayama*
15 Sep. 1997	15 09 38.3	16.2	551	−352.2	−0.0557	0.1399	218.8	272.4	Alma−Ata

Table 1. continued.

DATE	T_g^{Fit}	ΔX	IP^{Fit}	(O−C)IP	$\Delta\alpha\cos(\delta)$	$\Delta\delta$	$\phi1$	$\phi2$	PLACE
	UT	km	km	km	arcsec	arcsec	Deg	Deg	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
			3E2 events (continued)						
22 Sep. 1997	19 02 11.0	−45.0	2144	−12.7	−0.2147	0.5454	218.5	277.6	Bordeaux
22 Sep. 1997	19 02 04.8	18.1	2219	62.2	−0.2222	0.5644	218.5	277.6	Boskoop
22 Sep. 1997	19 02 11.4	−49.0	2149	−8.2	−0.2152	0.5465	218.5	277.6	Bucharest (S)
22 Sep. 1997	19 02 14.5	−81.3	2129	−28.0	−0.2131	0.5415	218.5	277.6	Bucharest (V)
22 Sep. 1997	19 02 10.1	−36.0	2116	−41.1	−0.2120	0.5381	218.5	277.6	Chateaugiron
22 Sep. 1997	19 02 10.3	−37.8	2183	26.3	−0.2187	0.5553	218.5	277.6	Meudon
22 Sep. 1997	19 02 11.9	−54.3	2184	27.4	−0.2187	0.5556	218.5	277.6	Munich
22 Sep. 1997	19 02 16.6	−102.9	2082	−74.4	−0.2087	0.5296	218.5	277.6	Prague
22 Sep. 1997	19 02 14.4	−80.3	2120	−37.2	−0.2122	0.5392	218.5	277.6	Reux
22 Sep. 1997	19 02 13.5	−70.2	2142	−14.9	−0.2145	0.5448	218.5	277.6	Ukkel−T85
22 Sep. 1997	19 02 14.9	−85.4	2123	−33.3	−0.2130	0.5400	218.5	277.6	Vainu Bappu Obs.
22 Sep. 1997	19 02 00.9	58.7	2102	−55.0	−0.2102	0.5348	218.5	277.6	Wilp−Achteroek
22 Sep. 1997	19 02 10.6	−40.9	2163	6.7	−0.2167	0.5503	218.5	277.6	Zaragoza
22 Sep. 1997	19 02 11.0	−45.0	2144	−12.7	−0.2147	0.5454	218.5	277.6	Bordeaux
22 Sep. 1997	19 02 11.9	−54.3	2184	27.4	−0.2187	0.5556	218.5	277.6	Munich
29 Sep. 1997	22 46 41.2	−77.2	3412	20.2	−0.3429	0.8678	217.9	282.3	Pic−du−Midi
			3O4 events						
21 May 1997	08 44 49.2	−418.7	1851	137.3	−0.1835	0.4952	77.3	34.0	Asheville
			3E4 events						
06 July 1997	22 32 26.2	−226.0	−2247	−241.1	0.2057	−0.5749	267.9	325.2	Catania (S)
06 July 1997	22 32 57.8	−452.6	−1931	70.4	0.1715	−0.4959	267.9	325.2	Torino
26 July 1997	01 53 33.3	−931.0	−5544	−206.1	0.4961	−1.4266	149.6	16.9	Catania*
10 Aug. 1997	11 16 37.7	80.1	−1430	−255.8	0.1292	−0.3679	202.6	347.3	Ellinbank
			4O1 events						
07 Oct. 1997	19 35 14.7	93.6	3254	−379.7	−0.3129	0.9483	172.0	38.7	Naucshny
			4E1 events						
03 Aug. 1997	00 05 03.9	−555.8	−567	14.4	0.0519	−0.1456	187.9	321.9	Comthurey
03 Aug. 1997	00 04 50.0	−244.7	15	600.6	−0.0013	0.0038	187.9	321.9	Grasse (B)
03 Aug. 1997	00 04 56.2	−385.2	−799	−213.8	0.0727	−0.2056	187.9	321.9	Grasse (V)
03 Aug. 1997	00 04 57.1	−410.6	−570	29.0	0.0563	−0.1450	187.9	321.9	Grasse (R)
03 Aug. 1997	00 05 02.9	−535.9	−836	−254.0	0.0747	−0.2155	187.9	321.9	Naucshny
03 Aug. 1997	00 04 57.6	−419.1	−306	276.5	0.0280	−0.0787	187.9	321.9	Praha
03 Aug. 1997	00 05 01.4	−501.6	−419	162.5	0.0380	−0.1078	187.9	321.9	Teide (T150, K)
			4O2 events						
24 April 1997	03 56 03.6	−783.6	149	58.2	−0.0149	0.0361	170.4	27.9	Bordeaux
24 April 1997	03 56 22.1	−1141.0	−170	−284.2	0.0074	−0.0440	170.4	27.9	Madrid
24 April 1997	03 56 05.2	−814.8	−542	−626.5	0.0442	−0.1354	170.4	27.9	Munich
24 April 1997	03 56 03.0	−775.7	19	−75.2	−0.0022	0.0046	170.4	27.9	Obs. Haute Provence
09 Nov. 1997	16 50 36.8	−706.2	2482	241.2	−0.2069	0.6542	159.7	99.4	Boskoop
			4E2 events						
30 June 1997	05 39 47.7	−689.5	−1797	−64.7	0.1572	−0.4636	182.5	353.0	New York
01 Aug. 1997	20 11 49.1	−617.2	3406	−2.9	−0.3050	0.8780	163.2	54.2	Vainu Bappu Obs.
			4E2 events						
12 May 1997	02 37 49.1	−432.0	−2754	75.5	0.2680	−0.7163	195.2	332.1	Boskoop
12 May 1997	02 37 57.3	−576.2	−2821	8.9	0.2745	−0.7337	195.2	332.1	Munich
19 Sep. 1997	22 15 05.2	−469.2	4083	104.7	−0.4196	1.2490	145.8	82.9	Bordeaux
19 Sep. 1997	22 14 30.0	−185.4	4406	426.8	−0.4528	1.3477	145.8	82.9	Ukkel
24 Oct. 1997	10 03 24.0	−606.6	−197	152.3	0.0191	−0.0541	169.7	18.5	Funaho

Table 1. continued.

DATE	T_g^{Fit}	ΔX	IP^{Fit}	(O−C)IP	$\Delta\alpha\cos(\delta)$	$\Delta\delta$	$\phi 1$	$\phi 2$	PLACE
	UT	km	km	km	arcsec	arcsec	Deg	Deg	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
			4E3 events						
01 Aug. 1997	00 21 03.7	−447.4	1328	27.1	−0.1226	0.3409	145.5	87.9	Barcelona
01 Aug. 1997	00 20 22.6	−164.7	1009	−290.4	−0.0931	0.2591	145.5	87.9	Catania
01 Aug. 1997	00 20 29.6	−214.3	1453	152.8	−0.1337	0.3730	145.5	87.9	Teide (T150, K)
01 Aug. 1997	00 19 44.6	106.5	1435	135.3	−0.1325	0.3684	145.5	87.9	Lisbon

Table 2. Residuals.

Ephemerides	Mean and rms of the residuals (arcsec)				Number of points	Sat. combinations
	RA		Dec			Model
	mean	rms res.	mean (O–C)	rms res.		
(1)	(2)	(3)	(4)	(5)	(6)	(7)
L1	−0.01336	0.05882	0.01638	0.07237	189	All Sat.
E5	−0.00030	0.06764	0.01055	0.07324		WOIV[1]
G5	−0.00204	0.06647	0.00849	0.07626		
E3	−0.00237	0.07837	0.00965	0.07503		
L1	−0.03470	0.05012	0.00089	0.06360	189	All Sat.
E5	−0.02164	0.05670	−0.00494	0.06363		WIV[2]
G5	−0.02338	0.05806	−0.00700	0.06660		
E3	−0.02371	0.06724	−0.00584	0.06533		
L1	−0.03286	0.05413	0.00400	0.06825	118	J1 with others
E5	−0.01314	0.05579	−0.00074	0.06815		WIV
G5	−0.00965	0.05908	−0.00079	0.06878		
E3	−0.01553	0.06091	−0.00122	0.06891		
L1	−0.02220	0.04560	−0.00135	0.05263	77	J2 with others
E5	−0.03419	0.05531	−0.01333	0.05365		WIV
G5	−0.04233	0.05059	−0.02045	0.05808		
E3	−0.03178	0.06776	−0.01455	0.05722		
L1	−0.04263	0.04602	−0.00150	0.06451	151	J3 with others
E5	−0.01483	0.05106	−0.00085	0.06344		WIV
G5	−0.02684	0.05401	−0.00533	0.06701		
E3	−0.00881	0.05691	0.00172	0.06340		
L1	−0.03412	0.05797	0.00615	0.06664	32	J4 with others
E5	−0.05495	0.07133	−0.01953	0.06712		WIV
G5	−0.01213	0.07430	−0.00545	0.07300		
E3	−0.10477	0.07505	−0.03761	0.06911		

[1] WOIV: Without considering the albedo variations
[2] WIV: With albedo variations from Voyager and Galileo imagery